CONDITION MONITORING OF INSULATORS UNDER POLLUTION

ABSTRACT
OF THE
THESIS

SUBMITTED FOR THE AWARD OF THE DEGREE OF

Doctor of Philosophy
IN
ELECTRICAL ENGINEERING

BY

ASFAR ALI KHAN

DEPARTMENT OF ELECTRICAL ENGINEERING
ALIGARH MUSLIM UNIVERSITY
ALIGARH (INDIA)

2009

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ABSTRACT

Cheap and reliable supply of electrical energy has been identified as an indicator of economic development and social welfare of any modern society. With increasing demand of electrical energy extensive networks of electrical power installations are being built at an ever increasing rate. The major function of such power systems is to generate, transport and distribute electrical energy over large areas which are different in topography, climate and environment in an economical manner while ensuring a high degree of reliability and quality of supply.

Increasing transmission voltages of EHV and UHV system place utmost importance upon the insulation integrity and reliability. Thus successful, reliable and uninterrupted operation of a modern power system depends to a great extent on reliable insulation. This insulation must not only withstand over voltages but must also provide satisfactory performance under different environmental conditions (pressure, temperature, humidity, wind velocity etc.).

The insulation of an overhead electric power transmission line is subjected to three basic types of abnormal conditions that may cause flashover and outages i.e. over voltages caused by lightning strokes, over voltages caused by line switching and abnormal voltage gradients in the insulation system caused by contamination of solid insulator surfaces. The relative severity of these three conditions vary with system operating voltage, with switching surges and contamination dominating on lines operating above 500 kV or so **[1][2]** .

Contamination on outdoor insulations enhances the chances of flashover. Under dry conditions, contaminated surfaces do not conduct so contamination is of little concern. Under conditions of light rain, fog or dew, surface contamination behaves electrolytically and starts facilitating flow of

leakage current. High current density near the electrodes results in the heating and drying of the pollution layer. An arc is initiated if the voltage stress across the insulators dry band exceeds it's withstand capability. Extension of the arc across the insulator ultimately results in flashover. The contamination severity determines the frequency and intensity of arcing and, thus, the probability of flashover.

To study insulator behavior under pollution and for improvement of insulator design proper testing under natural operating conditions is required. Adequate results are difficult to obtain from tests in natural conditions, and great efforts have been made to simulate pollution conditions by artificial tests. Before the development of artificial pollution test methods, the pollution characteristics of insulators could only be determined by recording insulator performance in conditions of natural pollution. Although such data are difficult to obtain, and are subject to much larger inherent errors than are the results of artificial tests, they are still essential for the validation and calibration of artificial test techniques, especially for new voltage levels and unusual types of insulators**[3]**.

The first overhead transmission line was designed in 1880's with 50 and 66 kV maximum operating voltage with porcelain insulators. Although great advancements in electrical technology has taken place in the last century but porcelain has remained as the main electrical insulator in large part of the world even today. Nonetheless the shape and size of porcelain insulators that are extensively used in majority of countries has seen considerable modifications. It is clear that for the proper understanding and design of insulators for different environmental conditions, it is necessary that extensive studies are undertaken. There have been number of studies in the last hundred years on ceramic as well as non-ceramic insulators. Almost all the studies revolve around electrical parameters such as flashover voltage, withstand voltage, leakage current, conductivity, chemical analysis of pollutants and salt deposit density.

No doubt the parameters of interest have remained the same, but the methodology involved in studying and understanding differed. Some researchers performed their study under natural conditions and others under artificial or simulated conditions. The studies under natural conditions have marked advantages and disadvantages **[4].** Keeping in view the rate at which power transmission system is growing, depending solely on natural method of testing will hamper the growth of insulation and its application technology. Therefore, testing insulators with artificial methods that approximates natural conditions have gained prominence. Also, since the actual contamination conditions are very complicated, the artificial contamination tests have made a greater progress than the study of field contamination **[5].** Thus tests are necessary for a proper judicious insulation design.

Once a suitable level of insulation design is achieved for a particular environment, it should not lead to complacency of the utility engineers because the suitability of the obtained design is bound to change due to increased population, industrialization and other factors. Moreover, ageing also leads to deterioration in the insulation behaviour of the material.

It is not always that the environmental pollution level increase, there are instances where due to, general awareness among the population towards pollution and improved technology of pollution control devices, substantial reduction in pollution levels have been achieved. For example reduction in dust precipitation has been observed in Poland, Germany, leading to change in leakage distance requirement from 2.6 cm/kV in 1987 to 1.3 cm/kV in 2002. It has also been reported that pH of rainwater has increased (from 5.6 towards 7) due to environmental improvement **[6][7].**Thus it is clear that if pollution characteristics of 1987 is taken for design of insulation level for a new installation in these countries, then it would result in over insulation. It is clear from foregoing discussion that continuous condition monitoring of

line insulators should be done to arrive at an economical leakage distance required.

Keeping in view the effect of pollution and its different nature, the present study was taken up to identify the pollution indicators already in use and suggest some new indicators/monitoring system to mitigate line failures due to insulation failure. Periodic monitoring of pollution levels with the help of new identified indicators can provide insight into the problem that pollution poses.. This is necessary because insulation requirement must be tailored to fit the needs of each specific case.

Apart from contamination, weather also plays a significant role in deciding the flashover performance of the insulators. A very recent grid failure of northern grid of India in March 2008 can be explained on the basis of dubious nexus of contaminants and prevailing weather condition. Normal winter rains did not occur during the period December 2007 and March 2008, thereby self cleaning of insulator surface did not occur leading to substantial deposits on the insulator. Apart from this, the relative humidity was very high during the first week of March 2008 and unusual fog conditions prevailed on 6^{th}, 7th and 8^{th} March 2008**[8],[9].**

In addition to the conclusions that will be given in paragraphs to follow, **the present study proposes pH of the contaminants as a new effective pollution severity indicator.** The effect of contaminant pH on flashover performance for both natural and artificial contaminant has been found to be quite significant **[10], [11].** The pH effect on flashover performance has not yet been investigated in detail; reports by Ramos **[5]** and Chrazn **[7]** have only slightly dealt this parameter.

Taking into consideration the North India grid failure of March 2008, the Power Grid Corporation of India started washing of power transmission lines using helicopters in November 2008. This hot line washing procedure was started as the winter rain forecast was not very encouraging. Around 82 million Indian rupees were spent for 300 flying hours for washing **[12].**

As already stated, the pH of the contaminant can be used as indicator of pollution severity. This pH can be used for continuous monitoring of overhead line insulators. It is suggested that hot line washing should only be started after the pH of the contaminant deposit exceeds the predetermined value. This predetermined value can be arrived at after detailed chemical analysis of the locational pollutants. Thus electric utilities should develop pH monitors that can relay signals to control stations so that maintenance engineers devise a proper maintenance schedule that is economical and serves the purpose of maintaining the reliable operation of the grid.

Based on extensive experimentation, both with natural and artificial pollutants the conclusions drawn are as given under:

1) For a fair and judicious insulation design/level, accurate knowledge of locational pollutants is important. Thus insulation requirement must be tailored fit for every location.
2) Detailed qualitative chemical analysis of pollutants in the area surrounding Aligarh lead to presence of Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, CO_3^{2-}, Cl^-, NO_3^{2-} and SO_4^{2-} (in dust and ground water), Cd, Cr, Pb, Fe, Cu, Ni, Zn, Mn (in soil due to ground water characteristics), fly ash and oxides of sulphur and nitrogen (due to thermal plant, brick kilns), particulates, CO, oxides of sulphur and nitrogen (due to vehicular emissions), phosphate and nitrates(due to agricultural fertilizers)
3) Insoluble component of deposits does not directly contribute to conductivity but aids in impediment of ionic movement, thereby leakage current.
4) The pH of the deposit and solvent affects the flashover characteristics.
5) Temperature, high RH affects withstand and flashover characteristics. Pressure in the present study remained almost constant in the range 742-745 mm of Hg.

6) Temperature affects viscosity of electrolytic solution and thus has an effect on withstand and flashover characteristics.
7) Higher RH leads to increase in availability of dissociated water molecules, thus affecting withstand and flashover characteristics.
8) Deposits with univalent cations have higher speed of movement (due to smaller ionic cloud density) than bivalent cations.
9) Ionic and hydrated radii affects withstand and flashover characteristics.
10) Solubility of salt also plays major role in deciding the withstand and flashover characteristics.
11) Transportation number affects leakage current flow.
12) For multi contaminant deposit, interaction of multi cation/ anion decides behaviour of insulation.
13) Activity coefficient of ions is also responsible for change in withstand and flashover characteristics due to addition of sparingly soluble/insoluble salt.
14) The flashover characteristics obtained after extensive experimentation with various soluble and insoluble salts leads to **proposition of a model that can be used for semi-arid/sub-tropical climatic zone such as Aligarh.**

The details of what has been summarized in the preceding paragraphs are detailed in the main body of the thesis.

Chapter 1 of the report deals with brief description of types of pollutants, insulating materials and the various prevalent standard tests. The chapter also details literature survey of relevant studies during last hundred years.

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In **chapter 5** detailed analyses and discussion on natural tests, artificial (semi-natural) tests is given. Also a model has been proposed for predicting flashover voltage values for insulators installed in semi-arid/sub tropical climatic zone. A comparison between experimental obtained values and predicted values is presented.

In chapter 6, the summary of results obtained, conclusions, research contribution and future work suggested has been reported.

It is hoped that this work will be of great use to practicing engineers and large power utilities.

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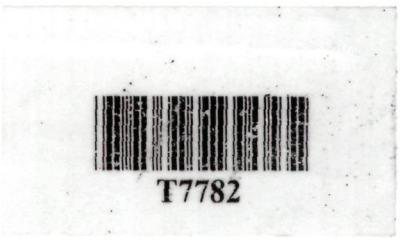

DEPARTMENT OF ELECTRICAL ENGINEERING
ALIGARH MUSLIM UNIVERSITY
ALIGARH-202002 (U.P.) INDIA

Dr. Ekram Husain
M.E., Ph.D (I.I.Sc, Bangalore), SM IEEE
PROFESSOR

Phone: +91-571- 2721178 (O)
Mobile: +91-9897151188
E-mail: ehusain2001@gmail.com

16, September, 2009

Certificate

This is to certify that the work embodied in this thesis entitled *"Condition Monitoring of Insulators Under Pollution"* submitted by Mr. Asfar Ali Khan is a record of his own work carried under my guidance and supervision. The work has not been submitted for award of any other degree. I wish him all the best for his future prospects.

16/09/09

Prof. Ekram Husain

DEPARTMENT OF ELECTRICAL ENGINEERING
ALIGARH MUSLIM UNIVERSITY
ALIGARH (INDIA) - 202002

Thesis Approval Sheet

The thesis entitled **"Condition Monitoring of Insulators Under Pollution"** submitted by **Mr. ASFAR ALI KHAN** is approved for the award of the degree of Doctor of Philosophy in Electrical Engineering.

(Internal Examiner) **(External Examiner)**

CHAIRMAN
Department of Electrical Engineering
Aligarh Muslim University
ALIGARH

Dedicated
to
My Grand Parents

CONTENTS

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Asfar Ali Khan

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DEFINITIONS

Some of the terms used in this thesis may appear new to an electrical engineering student. Effort has been made to define the different terms relevant to this work.

1) **Pollution:** Pollution is the release of chemical, physical, biological contaminants to the environment.

2) **Contaminants:** Contaminants or pollutants are substances which directly or indirectly affect the performance of something.

3) **Flashover:** When a disruptive discharge takes place between two electrodes of insulation, it is called flashover.

4) **Puncture**: The disruptive discharge that leads to ultimate failure of insulator and cannot regain its original properties is called puncture.

5) **Routine Test**: The object of this test is to detect manufacturing defects.

6) **Type Test**: The object of this test is to determine the characteristics of the insulators and its suitability for the service specified

7) **Insulators**: Insulator is a material or object which contains no moveable electrical charges. When a voltage is placed across an insulator, no charges flow so no electric current appears.

8) **Conductors:** Conductors are materials that contain moveable charges of electricity. When an electric potential difference is impressed across a conductor, the mobile charges within the conductor move, and an electric current appears.

9) **External Insulation** :The regions in air and the surfaces in contact with open air of solid insulation of the equipment, that are subjected to electric stresses and effects of atmospheric conditions, are called external insulation.

10) **Creepage Distance**: The minimum distance between two metal fittings on the insulator.

11) **Disruptive discharge voltage:** The voltage at which the electric field stress in the insulation causes a failure resulting in a collapse of voltage and passage of current.

12) **Reference atmospheric conditions:** The breakdown characteristics of insulation are generally referred in standards under reference atmospheric conditions of temperature, pressure and humidity. Most of the standards adopt following as reference:

Temperature - 20°C

Pressure - 760 mm Hg

Humidity - 11g/m^3 (65% RH at 20°C)

13) **Dry flashover test**: The test in which power frequency voltage is applied across an insulator, and is increased at a uniform rate till flashover occurs.

14) **Wet flashover voltage**: The test in which same procedure as above is adopted except that the insulator is subjected to artificial "rainy" condition.

15) **One minute Withstand Voltage**: The most common routine test used for porcelain insulators is the one minute dry and wet voltages withstand tests. In this test the specified test voltage (as per IS: 731 and IS 2099-1963) is applied, the specimen should withstand this voltage without flashover for one minute.

16) **FOVUID:** It is defined as flashover voltage per insulation distance, and is obtained by dividing the flashover voltage by the available leakage or creepage distance.

17) **WSVUID:** It is defined as withstand voltage per insulation distance, and is obtained by dividing the withstand voltage by the available leakage or creepage distance.

18) **Conductivity :** It is the measure of a materials ability to conduct

19) **Salinity:** The percentage salinity is the weight of salt in solution divided by the weight of the solution and multiplied by 100.

20) **Aqueous Solution:** An aqueous solution is a solution in which the solvent is water. In chemical equations it is shown as subscript (aq).

21) **Solubility:** Solubility is a physical property referring to the ability for a given substance, the solute, to dissolve in water.

22) **pH scale:** pH is defined as the negative logarithm of the hydrogen ion activity of the solution. pH values in aqueous solutions usually vary between 0 and 14 (pH <7for acidic, pH>7 for alkaline and pH=7 for neutral) and pH decreases with rise in temperature

23) **Ionic Radius:** Ionic radius may be defined as the effective distance from the nucleus of the ion to the point upto which it has an influence in the ionic bond. The ionic radius of a cation is smaller than that of parent atom while radius of anion is larger than that of parent atom.

24) **Hydrated Radius:** It is the radius of the ion after it gets hydrated.

25) **Lattice Energy:** The lattice energy of a crystal is the energy evolved when one gram molecule of the crystal is formed from gaseous ion. For example lattice energy of NaCl crystal is -782kJ/mol.

26) **Hydration energy:** The energy evolved when the ions of a metal get hydrated is called the hydration energy. For example hydration energy of sodium ion is -406kJ/mol while that potassium it is -330kJ/mol.

27) **Transportation Number:** The transportation number, also called transference number gives the fraction of the total current carried by a given ion in a solution.

Symbols and nomenclature

σ – Conductivity (μS)

ESDD- Equivalent salt deposit density (mg/cm^2)

FOVUID – Flashover voltage per unit insulation distance (kV/cm)

WSVUID – Withstand voltage per unit insulation distance (kV/cm)

NaCl - Sodium Chloride

KCl - Potassium Chloride

$CaCl_2$ - Calcium Chloride

$CaSO_4$ - Calcium Sulphate

Na_2SO_4 - Sodium Sulphate

$MgSO_4$ - Magnesium Sulphate

$NaNO_3$ - Sodium Nitrate

$Ca(NO_3)_2$ - Calcium Nitrate

$Mg(NO_3)_2$ - Magnesium Nitrate

CaO - Calcium Oxide

Chapter-1

Introduction

1.1 Introduction

The economic development and social welfare of any modern society depends upon the availability of a cheap and reliable supply of electrical energy. Around the world extensive networks of electrical power installations have already been built and are still being built at an ever increasing rate. The major function of such power systems is to generate, transport and distribute electrical energy over large areas which are different in topography, climate and environment in an economical manner while ensuring a high degree of reliability and quality of supply.

Increasing transmission voltages of EHV and UHV system place utmost importance upon the insulation integrity and reliability. Thus successful, reliable and uninterrupted operation of a modern power system depends to a great extent on reliable insulation. This insulation must not only withstand over voltages but must also provide satisfactory performance under different environmental conditions (pressure, temperature, humidity, wind velocity etc.) in all cases of disturbances such as flashover and/or line outages.

The insulation of an overhead electric power transmission line is subjected to three basic types of abnormal conditions that cause flashover and outages i.e. over voltages caused by lightning strokes, over voltages caused by line switching and abnormal voltage gradients in the insulation system caused by contamination of solid insulator surfaces. The relative severity of these three conditions vary with system operating voltage, with switching surges and contamination dominating on lines operating above 500 kV or so **[1][2]** .

The insulators used in overhead electrical power transmission lines are susceptible to contamination induced flashover. Outdoor insulators are subjected to pollution by dirt and chemical fumes in industrial areas, vehicular pollutants along roads, saline deposits near sea coast, desert salts as well as natural deposits. These pollutants in the presence of atmospheric

moisture, lead to deterioration of insulation capability and is responsible for high proportion of flashover that occur on a transmission system **[3] [4].** Apart from contamination by natural or industrial pollution additional sources of pollution are acid rains and gases- especially sulphuric acid and nitric acid (SO_X, NO_X). With heavily polluted areas, the surface conductivity on outdoor insulators can exceed the value of 100μS, which lead to arcing development and eventually to flashover at operating voltage **[5].** The resultant flashover and line outages represent large scale economic waste. Thus the problem of selecting suitable insulators for differently polluted locations is a pressing one. To study insulator behavior under pollution and for improvement of insulator design proper testing under natural operating conditions is required. Adequate results are difficult to obtain from tests in natural conditions, and great efforts have been made to simulate pollution conditions by artificial tests. Before the development of artificial pollution test methods, the pollution characteristics of insulators could only be determined by recording insulator performance in conditions of natural pollution. Although such data are difficult to obtain, and are subject to much larger inherent errors than are the results of artificial tests, they are still essential for the validation and calibration of artificial test techniques, especially for new voltage levels and unusual types of insulators**[6].**

The main objective of natural as well as the artificial pollution tests is to study the effect of pollutants on the withstand voltage, flashover voltage, conductivity of an insulator to arrive at an economical choice of insulation. Since the dry deposits usually do not lead to deterioration of the insulation capability of a given insulator, wetting is required for making the pollutants conducting thereby affecting insulation capability. The mechanism of wetting/moistening can be by natural means such as fog, rain, dew, mist, drizzle or by artificial means of producing moisture by clean fog, salt fog or direct wetting. Thus both the pollutants and moisture can either be natural or

artificial **[7] [8].** In wet conditions a partially conducting layer of pollution on an insulators surface can increase surface leakage currents and cause surface heating and dry band arcs. Higher pollution levels lead to eventful flashover of the insulator string. Insulators are designed to withstand a reasonable level of pollution under normal service conditions; however environmental factors can lead to an unacceptable level building up over time. A variety of conducting materials may pollute an insulator surface and affect its insulation characteristics **[9].**

Once the suitable level of insulation design is achieved for a particular environment, it should not lead to complacency of the utility engineers because the suitability of the obtained design is bound to change due to increased population, industrialization and other factors. Moreover, ageing also leads to deterioration in the insulation behaviour of the material.

It is not always that the environmental pollution level increase, there are instances where due to, general awareness among the population towards pollution and improved technology of pollution control devices, substantial reduction in pollution levels have been achieved. For example reduction in dust precipitation has been observed in Poland, Germany, leading to change in leakage distance requirement from 2.6 cm/kV in 1987 to 1.3 cm/kV in 2002. It has also been reported that pH of rainwater has increased; due to environmental improvement **[10][11].** Thus it is clear that if pollution characteristics of 1987 is taken for design of insulation level for a new installation in these countries, then it would result in over insulation.

It is clear from above that continuous condition monitoring of line insulators should be done to arrive at an economical leakage distance required. This can be achieved by monitoring the level of pollution periodically and also to look in for new parameters that can provide insight into the problem that pollution poses. Known indicators of pollution severity have to be supplemented with new indicators. This is necessary because due

to varied condition of weather, contamination etc. insulation requirement must be tailored to fit the needs of each specific case.

In the present work natural pollutant-natural wetting, artificial pollutant-natural wetting combinations have been taken to study the effect on flashover voltage, withstand voltage vis-à-vis pollution severity. Conductivity, ESDD, leakage current have been since long identified as indicators of pollution severity. This report will present an economical testing methodology that can be termed as semi-natural testing method, where wetting process has been achieved naturally without any artificial means. It will also be placed on record that pH of the contaminant also affects the insulation capability. Till date, this has not been investigated or reported much, only **Charzn [10] Ramos [12],** have touched this chemical parameter slightly. Apart from this, details regarding the chemical process that occurs for different salts have not been dealt thoroughly. Based on the chemical properties of various naturally occurring contaminants, the author has tried to explain the difference in mechanism that governs each salt species. An empirical expression relating flashover voltage to ESDD of the contaminant has been proposed. The results obtained from analysis are indicative of the facts that pH of the contaminants may require continuous monitoring in system operating under polluted environments.

1.2 Types of Pollutants

Pollutants or contaminants are substances which directly or indirectly affect the performance of a material, substance. Pollutants along with moisture adhering to line insulators affect their electrical performance and may lead to case of insulators turning into conductors **[13].** Impurities or pollutants suspended in atmosphere may be either insoluble, non-condensable inorganic matters of ultra microscopic size, heavy inorganic particles, organic materials that deposit or decompose and water vapour particles. The variety, size and distribution of airborne pollution particles are summarized in Table 1.1 **[6] [14].**

Table1.1

Nature of suspended matter		Diameter(micron)
Inorganic	Smokes	0.001 – 0.3
	Fumes	0.01 – 1.0
	Dust	1.0 -100.0
Organic	Bacteria	1.0 – 10.0
	Plant spores	10.0 – 20.0
	Pollens	15.0 – 50.0
Water	Fog	1.0 – 50.0
	Mist	50.0 -100.0
	Drizzle	100.0 – 400.0
	Rain	400.0 – 4000.0

The contaminants to be contended with are many and varied, both as regard to sourcing and materials. Sodium chloride is the most common material in the vicinity of sea coast or salt lake areas. Factory exhausts and agricultural fertilizers both contain electrically conductive chemicals. Desert sand, volcanic ash also contains conductive components. Bird excreta have also been found with conductive chemicals. Biological growths such as lichen have also been found in tropical rain forest areas. The different types of contaminants are summarized in Table 1.2 **[15].**

Table1.2

CONTAMINANTS	Sea Brine
	Rock salt, salt from salt lake
	Desert soil/sand
	Volcanic ashes
	Exhaust from factories
	Fertilizers, Insecticides, Ashes from burnt plants
	Bird Excreta
	Lichen

The chemical composition of the contaminants on insulator depends on the environment in which they are installed. Since pollution flashover is generally dependent on electrolytic effects, wherein the movement of ions causes flow of current that cause ultimate flashover. Owing to this the soluble ionizing component of the deposit is of greater interest than the insoluble **[16].**

1.2.1 Marine Contamination

Insulators in marine contamination area are most heavily contaminated by strong winds from the sea that carry predominantly sodium chloride (NaCl). Sea salt also contains magnesium chloride ($MgCl_2$) which is very hygroscopic material and thus sea salt absorbs moisture from atmosphere **[17].**

1.2.2 Inland Contamination

In the inland area the insulator is contaminated by sand or soil blown up by wind. The predominant soluble components of contaminants in an inland area are $CaSO_4$, $NaNO_3$, Ca $(NO_3)_2$. Small traces of NaCl, $MgCl_2$, Mg $(NO_3)_2$, $MgSO_4$, $CaCl_2$, KCl have also been found in certain areas **[18].**

1.2.3 Desert Contamination

In desert contamination area a large quantity of contaminants accumulate on insulator surface in absence of self cleaning due to scanty rain. The main soluble components in desert sand consist of NaCl, $CaSO_4$, and KCl. The quantity of NaCl is more in deserts that are near sea coast. Lime Powder (CaO) is the major non soluble contaminant. The problem gets compounded due to high humidity in coastal areas **[19].**

1.2.4 Industrial Contamination

Insulators used in industrial areas are contaminated by smoke, chimney ash and soot. The chemical compositions of contaminants vary depending on the kind of industry. For example a site near steel plant has $CaSO_4.1/2\ H_2O$ (Bassanite) as the major soluble component. Non soluble contaminants include SiO_2, Fe_2O_3, CaO, MgO and K_2O. A site near a coal

fired thermal power plant contains predominantly SiO_2 and other soluble components that may originate from dust or dirt **[20].**

1.2.5 Agricultural Contamination

In agricultural areas $CaSO_4$ has been found as the major soluble constituent. Agricultural fertilizers also contain electrically conductive chemicals/ions such as nitrates, phosphates etc. **[21].**

1.2.6 Biological Contaminants

Plant growth on insulators has been observed on bottom surface of insulators. Lichens are a plant group consisting of fungi and algae which live helping each other. Fungi take nutrients from algae while algae take nothing but water from fungi. Lichens grow on insulators in very wet conditions and take a long time. If these biological growths have salt, generally NaCl superimposed by any means, may lead to lowering of insulation strength **[15] [22].**

The various salts that have been listed in this section can also be classified based on their solubility. This classification given in Table 1.3 seems to be more relevant as due to electrolytic effects, the soluble ionizing components of pollutants are of greater importance **[12].**

Table 1.3

Highly Soluble Salts	$NaCl, KCl, CaCl_2, MgCl_2, NaNO_3, Ca(NO_3)_2$
Lowly Soluble Salts	$MgSO_4$, Na_2SO_4, Na_2CO_3 , K_2SO_4 , $CaCO_3$, $CaSO_4.2H_2O$, $MgCO_3$, $Ca_3(PO_4)_2$

1.3 Effect of Pollutants

The various pollutants that have been listed in section 1.2 are either soluble salts or insoluble salts. The dry pollutants are not a potential threat to the insulation capabilities. These dry pollutants when interact with water, which then behaves as an important pollutant **[6]**, forms electrolytic layer under drizzle, fog or other wet conditions. This conductive layer permits flow of current with the attendant ohmic heating and drying of the layer by

rapid evaporation of the moisture at locations of high current density. This phase is familiarly known as *'dry band formation'* **[23].** Most of the applied voltage now drops on these dry bands and gives rise to partial flashovers. These partial arcs propagate over the insulator surface and may, under certain conditions, eventually bridge the entire insulator by a process of several partial arcs; or, if the voltage is insufficient, the arcs may also extinguish at some point along the path of propagation, giving rise to so called scintillations **[24].**

The existence of insoluble pollutants is related to the water-hold capacity of insulators, and serves to worsen the voltage distribution of leakage path because of thermal drying due to leakage current **[25].**

1.4 Insulator Pollution and Flashover Mechanism

Insulators that operate in a contaminated environment as detailed in section 1.2 have reduced electrical strength and thereby flashover may occur, if the conditions are of aiding nature. The deposition of contaminants on an insulator surface is the first stage in the contamination flashover process.

1.4.1 Contamination Process

The principal processes which transport material on to the surfaces of insulators are gravitational forces, electrostatic attraction of electrically charged particles, evaporation of solutions or suspensions and aerodynamic catch, the last being of predominant importance.

When air containing suspended particles flows towards an insulator, the efficiency with which the insulator catches particles depend on the shape and surface finish of the insulator, size & density of the particles and the speed of flow. The insulator forces the flow to divide, leaving a stagnation point where the air is at rest. The flow changes direction away from the stagnation point, but the suspended particles, having densities greater than that of air, are unable to follow the flow accurately and pursue paths of lesser curvature. This motion relative to the surrounding air is resisted by the

viscous forces on the particles, however, and is small for low particle diameters and densities **[14].**

The simplest case of particle catch is thus the deposition of a relatively large, dense droplet or granule at a point of stagnation from which there is no force to remove it. Much more common and important, however, are the effects of rotating-flow or vortex generation, arising from the disturbance to the air flow introduced by the insulator. Vortices are produced at the sides of the insulator, which affect other insulators in its wake, and also within the underside structure of the insulator itself, especially by deep skirts or sheds. Rotating flow of this type gives rise to cyclone action: a given population of particles will be trapped in a rotating volume for many cycles, and the time for migration to the wall of the insulator, against the viscous forces, will be prolonged. Many quite small and low density particles will, in this way, be deposited and, moreover, actually within the convolutions. **[14]**

Once deposits have significant thickness they have the secondary effect of modifying the air flow, both by increasing the frictional drag and by causing subsidiary vortices. Heavily convoluted insulators may become clogged as a result of such cumulative catch, with disastrous effects on the electrical performance by the loss of effective creepage path.

1.4.2 Stages of the flashover process

The pollution flashover on insulators in actual service is preceded by following.

(i) Arrival of nearly pure water, as dew, rain, fog or mist at an insulator which carries a burden of pollution comprising soluble ionic components like common salt

(ii) Deposition of droplets from marine or industrial fog or of other combination of water and electrolyte.

(iii) Switching in of circuit containing insulators that are wet .

(iv) Arrival of a temporary over voltage or of switching surges at an insulator that is wet and possibly energized.

Of the above case (i) is the most common, especially in desert areas. Pollution flashover occurrence is closely correlated with time of dew and morning mist, while in marine polluted regions the dangerous times are in still-air fog.

1.5 Insulating Materials

From the viewpoint of flow of current, all substances may be classified as insulators and conductors. An insulator is a substance in which it is practically impossible to cause any current flow, since all the negative charges i.e. electrons are firmly attached to their corresponding positive charges and thus there is no net flow of charges (current). A conductor, on the other hand, is a substance in which a certain number of electrons can be easily made free from their associated positive charges, and made to move under the influence of an electrical potential difference. Under certain conditions free electrons and positive charges can also be made available in an insulating material, which then starts behaving like a conductor. Such a transition is known as the breakdown of the insulator. The mechanism of how an insulating material turns itself into a conducting one has been an area of study since last 100 years.

Electrical insulating materials are used in various forms to provide insulation for high voltage power networks. These insulators may exist in all the three states of matter viz. solid, liquid, gas and also composite forms. Solid insulating materials are used extensively in all types of electrical power networks, devices and substation equipment. Solid insulating materials should:

- have high dielectric strength
- have high mechanical strength
- be free from gaseous inclusions and moisture
- be resistant to thermal and chemical deterioration
- be insensitive to ambient conditions

Solid insulating materials may be classified based on their chemical composition as organic, inorganic and synthetic polymers. Inorganic materials such as ceramics and glass, owing to having the above properties are being used extensively as insulating material for power lines. Ceramics are inorganic materials produced by consolidating minerals into monolithic bodies by high temperature heat treatment. Low permittivity ceramics with relative permittivity less than twelve are generally used as insulators. Porcelain ($4K_2O.Al_2O_3.3SiO_2$) with relative permittivity of 8.5 was the primary material selected for the manufacture of the first power transmission line insulators in 1880's **[26]-[30].** It is still the most widely used insulating material for high voltage power lines, especially in India.

1.5.1 Testing of Porcelain Insulators

Porcelain as insulating material is used to maintain electrical insulation and support the mechanical load between a conductor and the ground in power delivery systems and power apparatus. This material should possess good insulating properties over a wide range of operating parameters since the reliability of the system depends on the condition of porcelain. To ensure satisfactory operation tests are required to be conducted on porcelain insulators **[31][32].** Various standards/specifications group the tests required under two categories

(i) Design or type tests, the object of which is to determine the characteristics of the insulators and its suitability for the service specified

(ii) Routine or manufacturers test, the object of which is to detect manufacturing defects.

As given in section 1.5 the insulators must fulfill the listed fundamental requirements. Corresponding to these requirements the basic electrical tests are as given below **[33] [121]**

- Dry flashover voltage test
- Wet flashover voltage test
- Dry one minute withstand voltage test

- Wet one minute withstand test
- Puncture test

High voltage insulators after undergoing above testing procedures are installed on various power lines. In actual service condition the insulators are exposed to varying environment as the power lines cross regions differing in topography, climate and environment. In addition outdoor insulators are also subjected to varying pollution levels owing to dirt and chemical fumes in industrial areas and saline deposits near the coast. These pollutants are responsible for high proportion of flashovers that occur on transmission lines and could cause the failure of the insulator string leading to major breakdown of the system covering a large area. To test the suitability of a particular insulator for a given pollution condition, it requires that the insulators are subjected to test under natural in-service conditions by energizing the insulator in various polluted areas at its nominal service voltage for a long time and record its behavior. This natural testing is time consuming as well as it may give scatter in the results obtained. Therefore a number of artificial tests have been developed with fair degree of approximation to the natural conditions.

1.5.1.1 Natural and Artificial Tests

The pollution characteristics of the design of insulators used in transmission systems are, in general, known only from service experience supplemented by tests on a few insulators in the laboratory or in naturally polluted sites. The performance of insulators can be assessed by natural pollution tests, which are imprecise but realistic, and by artificial tests, which are much more precise but less realistic **[34].** Before the development of artificial pollution test methods, the pollution characteristics of insulators could only be determined by recording insulator performance in conditions of natural pollution. Although such data are difficult and costly to obtain, and are subject to much larger inherent errors than are the results of artificial tests, they are still essential for the validation and calibration of artificial test techniques, especially for new voltage levels and unusual insulators **[6].**

Researchers have been constantly engaged in development of artificial tests that approximate the natural conditions to a fair degree of accuracy. There have been a number of artificial tests that suit a particular country and environment. The main artificial tests developed are detailed below.

1.5.1.2 Salt Fog Method

The salt fog method was first devised in Great Britain during early 1960's as a simple and direct method for assessing the withstand characteristics of insulators in saline atmosphere **[35] [36].** The salt-fog test is on of the two standardized test methods for ceramic and glass insulators described in IEC 60 507 **[37].**The test consists in subjecting a cleaned insulator to a salt water fog while it is energized at constant voltage. The fog is produced by arrays of nozzles on opposite side of the insulator, which direct a fog of droplets at the insulator by means of compressed air. The highest salinity at which at least three one hour tests out of four are withstood is called the withstand salinity and is regarded as the criteria of performance. Two ancillary tests that differ from the above in the means by which voltage is applied are also used. These tests save considerable time because the test voltage is raised after 20 minutes, from about 90% of the flashover value in steps of 2-2.5% at 5 minutes interval until flashover. The other is an "up-down method" in which test voltage is changed by 5% to obtain alternate flashover **[35].**

Although this method needs relatively long test durations, the salt-fog method has the merit that the testing itself is quite simple. It is very easy to achieve control within specified tolerance the parameters such as fog salinity, nozzle diameters, air pressure, and flow of solution. This test is also very good in repeatability and reproducibility.

1.5.1.3 Clean Fog Test

The concept of using a clean fog to deposit moisture on a contaminated string was first developed in Germany **[38].** The clean fog

method reflects the contamination mechanism of industrial areas away from the sea coast. This test is widely used in North America **[39] [40].**The insulators to be tested must be suitably prepared prior to contaminating. The surface of the glass and ceramic insulators should be cleaned of foreign deposits. Contamination is deposited by either dipping the insulator into the contaminant mixture or flooding the contaminant over the surface of the insulator. The contaminant mixture contains insoluble clay such as Roger's Kaolin or Tonoko and sufficient NaCl to obtain the desired ESDD on the insulators. The recommended concentration of clay is 40gm/litre of water. A minimum of one additional insulator should be contaminated for an ESDD measurement. In testing, voltage is applied to the insulator prior to fog and held constant for the duration of the test. The test is continued until either flashover occurs or in the event of a withstand at least twice the time that is required to reach minimum insulator wetting as determined by a low voltage leakage current test has elapsed. In order to adequately perform the test, a minimum transformer short circuit current of five amperes at the test voltage is required. A short circuit current of ten amperes may be necessary when testing insulators with an ESDD greater than $0.1mg/cm^2$ **[8]**. Warm or steam fog are the preferred method of producing fog although cold fog with chilled insulators is also acceptable as all these methods allow wetting by condensation **[39].** The up and down method is used for establishing the critical flashover voltage **[35]**.

1.5.1.4 Dry Salt Layer Method (DSL)

Dry Salt method has been developed from the principles of the present salt fog method and is intended to simulate flashover conditions close to the coast that can be described as the accumulation of semi-dry particles on the insulator followed by wetting in the form of rain or fog. Dry Salt method determines the ability of an insulator to withstand for a short time a specific environment at its operating voltage level.

Dry Salt method comprises a separate pollution deposition and wetting phase, voltage is applied during both the phases. Dry Salt layer method utilizes wind as the driving force to deposit humid salt particles on to the test object. The humid salt particles are generated by a salt injection system. The salt spray is, however, not directed towards the test object as in the salt fog method. Its purpose is rather to suspend humid salt particles in the air flow established in the laboratory chamber during the test. The wetting phase utilizes a steam fog and lasts for 100 minutes. During the test the parameter recorded is flashover or withstand voltage, SDD, leakage current and hydrophobicity **[41].**

1.6 Brief Literature Survey

Porcelain as an insulator for power lines has been in use since 1880's. Since the earliest days of power transmission, contamination flashover has plagued overhead transmission lines. Flashover triggered by early morning dew deposits were noted as early as in 1902. Systematic research into the causes of contamination flashover appears to have begun with Anfossi's study in 1907. During last 100 years there have been number of reporting by independent researchers and various utilities relating to testing of insulators under various natural and simulated conditions. This section gives an overview of reported literature during 1907-2009 in brief.

J. Lustgarten, 1912[42] remarked that porcelain is eminently suitable for permanent exposed insulation. He listed the properties of porcelain and its constituent's i.e. kaolin, silica, feldspar. The purpose of glazing according to Lustgarten is to fill the superficial irregularities that may lead to absorbing of dirt, soot etc. He further related puncture voltage to thickness of porcelain and suggested almost linear relationship for the same. Experiments were conducted to show that sparking between two electrodes on a surface does not depend upon the surface resistance except when moisture is deposited. Effect of humidity on flashover was studied and lower flashover voltages were obtained at 100% humidity. It was also reported that

temperature has little effect, as the spark-over voltage varies inversely with absolute temperature **[43].** A variation of 2.4% in flashover voltage was observed for variation of 10mm atmospheric pressure.

B.L. Goodlet, 1929[33] listed the various electrical and mechanical tests to be performed on porcelain insulators. He studied the influence of atmospheric humidity on spark-over voltage and concluded that above 90% relative humidity the spark-over voltage generally begins to fall; the actual precipitation of moisture on the insulator surface lowers the spark-over voltage. Goodlet also noted that the performance of an insulator in the fouled condition cannot be characterized solely on the basis of its spark-over voltage. The action of arc discharges, if prolonged is very damaging to the surface and glaze of the insulator. He further concluded that insulation troubles in transmission systems are invariably due to excessive voltages, reduced insulation strength or mechanical failure. Reduction in the insulation strength may be caused either by adverse surface conditions such as rain, fouling or by damage of a mechanical nature such as fracture of the sheds. He opined that it must be realized that it is neither possible nor desirable to devise tests which will cater for every possible source of trouble.

J.S. Forrest, 1936[44] defined the term "*leakage current*" of an insulator chain as the current flowing through the earthed end of the insulator chain. According to Forrest, leakage current, in addition to being a rational criterion of insulator performance, is subject to easy and rapid measurement by means of simple instruments. He further found that the steady value of the leakage current of an insulator chain varies between 0.2 to 1.0 mA, depending on the weather conditions. In fog or with dirty insulators under humid conditions surging takes place and current reaches about 100 mA. During testing of insulators under wet weather conditions i.e. foggy conditions in industrial area a new phenomenon termed as "*fog surging*" takes place.

Forrest [44] explained the mechanism of fog surging as: The effect of fog in industrial districts is to deposit a dirty film on the surface of the insulator in the presence of a saturated atmosphere. This film gives rise to the cumulative production of local discharges on the surface of the porcelain, and these discharges increase in intensity on the individual units until a relatively intense discharge occurs over the whole chain. This is fog surge and its heating effect leads to drying of the surface film and insulator surface returns to its former condition. The complete flashover of the insulator chain occurs when exceptionally severe surge is repeated.

I.S. Scott-Maxwell, 1936 [45] enumerated the various reasons for flashover, one such cause being fog, mist and dirt deposits. He noted that the greatest amount of dirt collects on the under-surface, and, owing to the corrugations being underneath, the greater percentage of the surface area thus became contaminated. This contamination may lead to corona and streamer discharges appearing around the upper end of the pin and between the bottom edge of the cap and the porcelain. The size to which these streamers grow and voltage at which they appear depends chiefly on the state of the insulator with regard to cleanliness & moisture, shape of the porcelain, pressure, temperature, humidity of surrounding air and the voltage applied to the strings.

W.J. John and C.H.W Clark, 1939 [46] listed the various solid deposits as products of combustion of coal, cement, metallic salts, sea salts. They inferred that when an insulator surface has a heavy industrial or salt deposit and is moist, flashover of the insulator often takes place at working voltage. They were also of the opinion that tests made under natural conditions are slow in yielding results, and it would be helpful if laboratory methods of testing were available. They developed a standard saline deposit test for insulators and suggested dew formation in laboratory by ice box method.

In another very important work, **J.S. Forrest, 1942[47]** remarked that if large power systems are to be operated with a minimum of breakdowns a carefully planned scheme of field testing, supplemented by laboratory investigation, is essential. He suggested that an important indication of the performance of an insulator is given by leakage current. The mechanism of insulator flashover under deposit conditions was thoroughly investigated. Radio noise caught attention in 1932, when the radio noise level due to corona discharges on a 66 KV pin type insulator was measured for the first time **[48]. Forrest [47]** observed that if discharges become more intense owing to humid weather or dirty insulators the intensity of the electromagnetic radiation increases, and may interfere with the reception of radio signals and this was a problem attracting serious consideration in those times where communication networks were developing. Now it can be said without any fear of contradiction that the concerns were real and true.

W.G. Thompson, 1944 [14] studied the nature of air-borne particles and the forces acting upon them to analyze the mechanism of contamination of porcelain insulators. According to Thompson impurities suspended in the atmosphere can be classified as permanent or temporary suspensions. The permanent group comprises the insoluble and non-condensable inorganic matter of ultra-microscopic size, which is maintained in suspension by the kinetic forces of the moving gas molecules and can be precipitated only by electrical means. The temporary suspensions include the heavy inorganic particles which ultimately deposit by gravitation, the organic material which either deposits or decomposes and water vapor particles which either condense or disperse according to the temperature and wind conditions. The forces acting upon the air borne particles are kinetic, gravitational, electrical and aerodynamic. **Miller [49], Thompson [14], Lambeth [6]** classified suspended particles in atmosphere based on their nature and size as given in section 1.2. Thompson studied the three types of air flow to which insulator is subjected. The three flows viz. laminar, high speed eddies and slowly

moving eddies make characteristics contribution to deposition of foreign matter on the surface of the insulator. The factors involved in the final retention of the particles at the insulator surface are the boundary layer of still air at the surface, surface roughness, applied voltage and the humidity. He further classified moisture films as

(i) the surface film which is present even in dry weather

(ii) the film produced as a result of temperature differences between the insulator and the surrounding air

(iii) the film which forms on the insulator

(iv) the surface wetting produced by drizzle and rain.

The conjunction of these films and deposits may become good conductor and thus may cause flashover.

Forrest 1960 [23], in his famous reporting on insulator performance in polluted environment suggested that electrolytic conductive layer permits flow of current with the attendant ohmic heating and drying of the layer by rapid evaporation of the moisture at locations of high current density. This phase was termed as *'dry band formation'* and presented a picture that is still being used to understand the performance of polluted insulators.

L.L. Alston and S. Zoledziowski, 1963 [50] studied the growth of discharges on polluted insulator and concluded that discharges do not necessarily lead to a flashover, and polluted insulators often exhibit sparks which extinguish after having spanned over only a fraction of the insulator surface. According to them as the discharges grow; they reach a critical length at which the voltage required to maintain conduction between the terminals of the insulator exceeds the supply voltage. A relationship for the condition in which flashover is impossible was suggested; it related maximum current which can flow on an insulator energized at a particular stress. The criterion was validated by experiments and work done earlier by **Forrest etal [23]** and an **AIEE committee report [51].**

Zaazou, Khalifa, 1964 [52] studied the effect of atmospheric humidity, surface pollution on radio noise due to corona. They reported that radio noise level is found to increase with the air humidity and decrease if the insulator is kept in a humid atmosphere for some time. It was also concluded that the cement binding the metal cap and pin to the porcelain is found to be the main source of noise when the insulator is under corona discharge.

Hampton, 1964[53] studied the surface discharges that occur due presence of moisture on contaminated high voltage insulators. The voltage distribution along the wet polluted surface was measured and the method of formation of dry bands clarified. The formation of dry band was reported by **Forrest [23]** as described earlier.

Ely and Lambeth, 1964[3] developed a new method of measuring the performance of an insulator subjected to artificial pollution. A saline fog was produced in which the insulator flashes over at its working voltage. The salinity of the aqueous solution used for fog is reduced and the maximum value at which the insulator will not flashover was obtained. It was concluded that this salinity be taken as criterion of performance. They suggested that this artificial pollution method be proposed for use as a standard test.

Lambeth, Looms et al, 1966 [54] suggested principal remedial measures so as to contain pollution flashover leading to outages. According to Lambeth et al pollution flashover is known to be preceded by formation of electrolytic film. To get rid of unwanted flashover he suggested that attempts be made to prevent the formation of this continuous film. They suggested that apart from washing, long leakage path be provided so that formation of conducting film gets inhibited. It was suggested that this inhibition could be achieved by coatings of grease and oils. Silicone oils and polymers were used in 1940's. Silicone greases were also used **[23] [55], [56], [57].**

M.J. Billings and R.Wilkins, 1966[57], suggested that in order to improve flashover performance and reduce radio frequency noise resistive glazes be used on porcelain insulators. The resistive glazes give 'voltage stabilization' effect.

J.K. Dillard, et al, 1966[1] in a status report on design of EHV transmission line listed the three basic types of abnormal conditions that cause flashover. They were of the opinion that the relative severity of these three conditions varies with system operating voltage, with switching surges and contamination dominating above 500 kV.

Khalifa and Morris, 1967 [58] studied the performance of suspension insulators under rime ice. Rime ice of various densities was deposited and the increase of leakage currents, the reduction of flashover voltages and the alteration of voltage distributions along insulator strings caused by presence of ice were measured. Rime ice was produced in the laboratory and its electrical conductivity was measured and was found to increase with the ice density and temperature. The voltage of the rime ice deposited insulator was increased and at some voltage numerous discharges began to occur within the rime ice. Due to heating effect of leakage currents, the ice began to melt and arcs were formed, some arcs persisted and ultimately complete flashover of insulator ensued.

Kadowaki et al,1968[59] carried studies in Japan during the period when both steam and electric locomotives ran on the same track, there were situations when the ceramic insulators used on the track were contaminated by soot from steam engine. The leakage current on the insulation due to this contamination was studied.

According to **Tominaga, 1968 [60]** flashover on the insulators of power transmission system occurs due to spray of sea water on insulators and also due to moistened dust. **Nakazima [61] and Akazaki [62]** studied the above two cases and concluded that flashover occurs due to heat on the

insulator surface. Tominaga studied the arc produced on the contaminated ebonite plates and concluded that flashover occurs due to heat.

Ely and Roberts, 1968 [13] studied the switching impulse behavior of suspension insulators to pollution severity. They concluded that greater reduction in flashover voltage of insulator was observed for given salinity if duration of switching impulse was longer. The decrease in voltage is proportional to log (salinity).

A.G Goldring et al, 1969 [63] reported the development of ceramic and synthetic insulators on high voltage ac electrification system on British railways. The operational difficulties were due to severe pollution from steam locomotives. Initially the minimum creepage distance was 1070 mm but as steam locomotives disappeared this large creepage distance was reduced to 790 mm and further reduction was expected.

R. Wilkins, 1969 [4] observed that contamination on the surface of high voltage outdoor insulators can lead to the formation of quasistable gas discharges, which burn in series with resistive contaminative film. Under certain conditions these surface discharges can grow to produce a complete insulator flashover. Wilkins introduced a model for the case of a discharge burning on a rectangular polluted strip. A factor which accounted for the change in resistance due to heating has been calculated.

M. Kawai and D.M.Milone, 1969 [7] classified pollution condition into categories as salt contamination and industrial pollution. Salt contamination initiated flashover is caused directly by salt from sea water carried by strong winds and also when salt deposited on a porcelain surface gradually absorbs moisture. Industrially polluted insulator flashovers are similar to latter type of salt contaminated flashover except for difference in the nature of conductive materials on the porcelain surface. Kawai used steam fog method that produces slow wetting condition and represents good method of contamination testing because of its similarity to natural condition. It was also found that the critical flashover voltage of salt

contaminated insulator to be a function of both salt and insoluble materials present. It was also reported that linearity between flashover and insulator length in low salt deposit density area is questionable. Kawai performed similar tests in Japan as he was of the opinion that 'equivalent fog test' prevalent in Japan lacked true simulation of natural conditions.

B. Macchiaroli and F.J.Turner,1969 [8] were of the opinion that artificial contamination tests being employed were generally designed for specific natural conditions and required expensive facilities and so they proposed a new contamination method that could be applied in any existing laboratory without adding expensive new facilities or equipment. B.Macchiaroli et al considered two philosophies that could be followed for contaminating an insulator (i) putting contaminant selectively in a manner simulating natural conditions (ii) to produce uniform coat on the entire surface. Uniform coating technique was used and preparation of insulator for test was also outlined. In the proposed "wet contamination method" the test was conducted while the insulators were still wet, three to five minutes after the end of the flow-coating process. They also proposed a standard slurry obtained from hydrolysis of silicon tetrachloride as it is almost 99% pure and also has same physical and chemical properties at all locations. It was also concluded that surface conductivity of insulators should be used to measure the degree of contamination.

Alan J. Mcelroy, et al, 1970[64], studied insulators with contaminated surface in Ohio state. The physical and chemical analyses was done on suspension insulators and was found that $CaSO_4$ (gypsum) was the major soluble surface deposit and alpha quartz the insoluble component. A laboratory simulation system was used to produce flashover on a single suspension insulator with contamination conditions and voltage as experienced in field. The insulator surface was contaminated by three basic substances: inert insoluble material (bentonite), soluble substance ($CaSO_4$) and water (fog) to render the surface conducting. The leakage current was

recorded using strip chart recorder, discharge current was monitored by oscillograph. Clean fog method was not found suitable for industrially polluted area as the fog sample in Ohio had considerable dissolved salt and hence salt fog test was thought to be better way of simulating fog that occurs in industrial areas.

According to **B. Macchiaroli and F.J. Turner, 1970 [38]** since under natural service condition forces such as rain, gravity, electric field combine to produce a highly non-uniform coating, the effect of such a non-uniformity of contaminating coating was studied. It was reported that a non-uniform distribution of contaminant along an insulator string results in a lower flashover strength than a uniform distribution. They also studied the effects of geometrical position of a contaminated string and reported that due to greater tendency of horizontal strings to clean them by washing, could result in apparently greater strengths in field installations.

M. Kawai and D.M. Milone, 1970 [65] conducted experimental studies on the contamination flashover strength of insulators having different shapes and different mechanical strengths. The test procedure is same as done by **Kawai et al [7].** It was concluded that different contaminating slurries be used for complete evaluation of insulator performance. They also observed non-linearity of insulation strength with insulator length.

T. Fujimura, M.Okayma, T.Isozaki, 1970 [66] were of the opinion that though antipollution designs of insulators could effectively improve their performance under pollution but may not be practical because pollution sometimes advances to very extreme extent. They suggested that hot line washing is a very positive and economical countermeasure against pollution. They also concluded that washing withstand voltage of insulators should be carefully investigated before actual hot line washing since electrical properties of insulators are influenced by precipitation, water resistivity and wind condition.

McElroy, et al 1970[67], studied the electrical discharge mechanisms as they occured across relatively dry zones on wet contaminated insulator surfaces. They gave a mathematical model for the same with the assumption of constant surface resistivity. It was found that the theoretical and experimental results were in disagreement, probably due to non-uniformity of surface resistivity that existed on insulators.

H.J. West, J.E. Brown and A.L. Kinyon, 1971[68] studied unexpected flashovers that caused 32 outages on the Bonneville Power Administration 500 KV ac line. The insulators installed on the line were removed from service and tested in laboratory but seldom showed typical flashover tracking. One of the specimens had heavy bird contamination and so West et al came to the conclusion of "The Bird Theory" being responsible for flashover. The excrement samples were tested and it was found that the material was alkaline and had resistivity between 30 -120 Ω-cm. They developed a bird simulator for simulation of EHV transmission line flashover initiated by bird excretion.

Ely, Kingston, Lambeth, 1971 [34] were of the opinion that performance of insulators could be assessed by natural pollution tests which are imprecise but realistic and by artificial tests which are much more precise but less realistic. They performed pollution test on 400KV substation insulator using both natural and artificial pollution methods. They found good correlation between the two tests. A linear relationship between logarithmic of flashover voltage and salinity was arrived at.

B. Macchiaroli and M. Rea, 1971 [69] carried tests to analyze the influence of geometrical and physical parameters of a contaminating layer on the flashover of small flat surface. The test results showed that the flashover voltage of a polluted strip depends strongly on the surface conductivity and slightly on the layer width and thickness. They were of the opinion that extension of these conclusions to actual insulator needs the extrapolation of test conditions.

Lambeth, 1971 [6] remarked that high voltage insulators may flashover at working voltage when polluted and wet. There are number of forces such as kinetic, gravitational, aerodynamic etc. that lead to deposition of pollution **[13].** Lambeth was of the opinion that water is itself an important pollutant, since, without it, nearly all solid pollution would be non- conducting. The processes involved in pollution were studied by analyzing voltage distribution on a polluted strip. The effect of electric stress on wet pollution layer was studied with sodium-chloride solution and sulphuric acid.

An **IEEE working group with E. Nasser as chairman, 1971 [70]** conducted a survey with the help of questionnaires sent to 90 utilities (i) to determine the nature and extent of insulator contamination problem in US and Canada (ii) to determine what corrective measures have been taken to alleviate the problem and how successful they have been. After receiving the responses the group, listed about 30 contaminants as given in Table 2.1**[70].** The group was surprised to discover that fog is not the most frequent and severe deteriorating factor but drizzle & mist are worse. Dew was found to be third most severe wetting agent. The group on the basis of reply to questionnaires summarized the preventive measures taken. It was found that silicone grease was most frequently used (57%) measure followed by washing (17%), increase of insulation (9%), use of different insulator type (7%) and use of petroleum jelly (4%)

R. Wilkins and A.A.J Baghdadi, 1971 [71] carried experimental work with simple models to investigate the conditions under which arc propagation occurs. Under wet polluted surface conditions, arcs may be formed on the surface of high voltage insulators. These arcs result from the interruption of the leakage current when dry bands are formed on the surface. The arcs may elongate under certain conditions and total flashover may occur.

I. Kimoto et al, 1971 [25] presented anti-pollution design criteria for line and suspension insulators. For examining countermeasures for insulator pollution the actual pollution condition and degree of pollution must be known. Insulator pollution is classified as ordinary salt pollution, rapid salt pollution, industrial salt pollution. Kimoto et al installed pilot insulators of 254 mm dimensions in above classified areas and measured ESDD weekly, monthly, quarterly, bi-annually and annually. Artificial fog withstand test was used to simulate pollution flashover process of insulators in naturally polluted atmosphere by using slurry of NaCl and kaolin deposited uniformly, dried ,installed in fog chamber and fog withstand characteristics investigated. Kimoto et al concluded that practical design criteria of insulation for specific pollution areas is obtained by combining the survey results in field and investigation results in laboratory.

P. Claverie, 1971 [72], conducted theoretical and experimental study of the flashover mechanism on polluted insulation under ac voltage for insulating plate of simple geometry. A general relation between voltage, maximum leakage current and maximum arc length was proposed. This proposition could be extended and knowledge of resistances in series with the arc could be used to determine the flashover voltage. The results obtained could be applied to different types of line insulators.

Jolly, 1972 [73], studied the physical processes involved in flashover of contaminated insulator and reviewed various theories of discharge propagation proposed by Hampton **[53]** Wilkins **[71]** etc. He found the theories unsatisfactory as they were unable to account for the high speeds of discharge elongation. It was proposed that under certain conditions contamination flashover is an electrical breakdown process as the electrostatic force dominates over electromagnetic and thermal forces.

Lambeth, et al, 1973[35] by means of comparisons between laboratory results and results obtained in natural environments concluded that the behavior of insulators in salt fog is very similar to behavior of

insulators in representative types of natural conditions. This report was result of a collaborative programme of national electric agencies of Great Britain, France, and Italy for refining and validation of salt fog test to establish repeatability and reproducibility. The general rules were deduced for performance in relevant pollution as:

(i) Length of string and flashover voltage in a given severity are directly proportional

(ii) Withstand salinity α S^{-p} where $p \sim 0.2$

(iii) Flashover α Creepage path length

(iv) Withstand salinity was regarded as criterion of performance

Williams et al, 1974[18], performed laboratory experiments with nine salts, NaCl, $NaNO_3$, Na_2SO_4, $MgCl_2$, $Mg(NO_3)_2$, $MgSO_4$, $CaCl_2$, $Ca(NO_3)_2$, $CaSO_4$ as contaminants on flat plate insulators and measured flashover voltage. The results suggested a dependence of flashover on the type of contaminant as well as ESDD. A relationship was proposed that related limiting flashover voltage to ESD as

$$LFOV = [\, V_0 (ESD)^{-p}]$$

It was also obtained that solubility has negligible dependence on LFOV but was concluded that more soluble the salt, sooner it will form a conducting electrolyte with resulting flashover. They were also of the opinion that heavier ions yield higher flashover voltage. Salt migration effect was also observed, Permeation theory may explain higher flashover voltage for heavier ions as they diffuse more slowly.

G. Karady, 1975[39], studied the effect of fog parameter on artificially contaminated insulator. Series of experimental tests conducted showed that the flashover voltage, washing effect of fog and leakage current all depend on the fog conditions. The study analyzed the mechanism of wetting process by determining the rate of water accumulation on an insulator surface together with the variation of the surface resistance and flashover voltage with different fog conditions. It was concluded that in case

of cold fog, the major wetting is due to collision of water droplets, for steam fog its condensation and for warm fog both condensation and collision of water droplets with insulator contribute to the wetting.

F. Rizk, et al 1975[74], reported laboratory and field experiences with EHV transmission line insulators in desert. They concluded that contamination layer build up is a slow and gradual process, that soluble salts may be up to 20% by weight, relative humidity above 90% may pose serious hazard to a contaminated insulator. Rizk et al were of the opinion that higher relative humidity accelerates wetting process; this wetting process depends on the nature of inert binder in the contaminant which in turn influences the flashover voltage.

Holte et al, 1976 [75], studied the dependence of flashover voltage of a strip on the chemical composition of multi-component salts. They extended the work done earlier **[18]** for single salts and proposed an equation that related LFOV of multi salt contamination to individual LFOV of the components at individual ESD'S. They were of the opinion that conductivity can be measure of contamination severity for single salts but may give ambiguous results for multi salts. Resistance as a measure of contamination severity is hard to determine and therefore they proposed method of utilizing ESD and chemical analysis of the contaminants as a standard method for multi- salts. They also extended this method to suspension insulators and related LFOV of plate to LFOV of suspension insulator

C.T. Wu and T.C.Cheng, 1978 [76], proposed a new coating technique for artificial contamination test called "Fog Deposition Method". This technique was different from conventional artificial contamination procedures and produces a uniform coating which is superior over the usual brushing, dip-dry or flowing coating methods **[77].**

H.M. Schneider & C.W. Nicholls, 1978[78], conducted contamination tests on suspension insulators up to $1450/\sqrt{3}$ kV. They found

that contamination flashover voltage is non-linear function of string length. Cold switch-on performance of conventional and semi-conducting glaze insulators for UHV was studied and was found to be nearly same.

T.C. Cheng & C.T. Wu, 1979 [79], reported a study on mechanism of breakdown of an insulator surface contaminated with different species of salt. Cheng & Wu were of the opinion that if NaCl alone was used to study the flashover phenomena, its scope would be narrow and other important electrochemical reactions may be overlooked. They performed tests with variety of salts and found that nitrates can inflict very detrimental effect on glass insulators. They found that the glass surface was badly etched and etchings resembled Lichtenberg figures. The effect of $NaNO_3$ was more severe than $Ca(NO_3)_2$. It was also reported that effect of nitrates on porcelain was less severe.

IEEE working group on insulator contamination chaired by **K.C. Holte, 1979 [17]** combined the experiences of electric utilities, manufactures and research laboratories vis-à-vis design and maintenance of transmission insulation in a contaminated environment. The report explained the formation of dry band, usually formed near the cap of a suspension insulator. This leads to increase of resistance and therefore concentration of voltage stress across them causing small intermittent scintillating discharges bridging the dry band. These discharges may elongate and bridge the entire insulator. They classified the contaminant as conductive and inert. Conductive contaminants consist of ionic salts such as NaCl, Na_2SO_4, $MgCl_2$, etc. or soluble gases such as SO_2 provide a conductive coating when in solution and may lower electrical withstand strength. The inert components such as SiO_2, clay, cement etc. though do not go in solution may catch ionic impurities and lower electrical withstand strength. Insulator wetting was listed as the other factor that determines site severity. The methods employed for measuring site severity were:

(i) conductivity measurement by removing contaminant i.e. ESDD measurement

(ii) conductivity measurement without removing contaminant

(iii) chemical analysis or cation/ anion analysis

(iv) leakage current measurement

(v) use of directional dust deposit gauge

A method of calculating ESDD was also explained. The performance of contaminated insulator may be obtained from data/records of in service lines or may be subjected to any of the three artificial test i.e. salt fog test, clean fog test or wet contaminant test. The group summarized the factors and considerations involved in designing an insulator for contaminated conditions. Guidelines were also listed for practice to be adopted for insulator maintenance.

K.J. Llyod, 1981 [80], presented an overview of past work and work in progress vis a vis testing contaminated insulators at project UHV. It was suggested that similar to HVAC, full scale testing using actual system voltage must be done for HVDC also. The dust method of contamination was suggested, wherein charged dust is blown in the area of insulator testing.

M.P. Verma and W. Petrusch, 1981 [81], reported results of pollution tests on insulators for voltages above 1100kV. They were of the opinion that results of pollution tests depend on many factors such as modes of applying pollution, wetting and test voltage. Different short circuit current at different voltages could also influence the results differently.

IEEE taskforce on testing IEEE insulators, 1983 [82], in order to standardize the clean fog test, used tests conducted by eleven laboratories on a common IEEE insulator (leakage distance 305mm). In spite of the fact that standard guidelines were used, yet there was dispersion in the result, probably due to differences in the testing sources, characteristics, the variation in contamination deposit and fog wetting rate. Thus the task force

concluded that to make this test a standard contamination test stringent guidelines are needed.

K. Naito, et al, 1983[83], investigated characteristics of natural fog condition in the field and that of artificial fog condition in fog room. The measured values of natural fog condition was compared and influence of artificial fog condition on withstand voltages was studied. They recommended fog condition to obtain good reproducibility of natural fog condition. The kind of fog, fog density, droplet size of fog and temperature of fog room was enumerated.

S. Gopal et al, 1984[24] proposed a new mathematical model based on a dynamic arc voltage gradient equation and compared those with other models **[84], [85]** and found good agreement. This model was based on '*dry band formation*', scintillations and cascading of several partial arcs/ flashovers.

M. Ishii et al, 1984[86], studied the effect of ambient temperature on the performance of contaminated DC insulators. Experiments conducted indicated that for a given salinity of contaminating solution, the amount of salt contained in the contaminated surface is strongly temperature dependent. This dependence was attributed to the viscosity- temperature characteristics of electrolytic solution, at higher temperature viscosity of water reduces and thus contamination layer is thin (less salt in the layer). ESDD at 35^0C is lower by about 20% than ESDD at 5^0C. The residual resistance of a contaminated surface reduces considerably with increasing temperature and therefore to have a given resistivity, the amount of salt required at higher temperature is less than that at lower temperature.

K. Chrazn, 1987 [87] presented in his study, an analysis of the conductivity of aqueous solutions of dusts occurring in the atmosphere and its effect on outdoor high voltage insulation. Chrazn listed the chemical compounds, varying in their solubility, occurring in dusts such as insoluble oxides, weakly soluble carbonates, sulphides, fully soluble sulphates,

nitrates, chlorides and hydroxides. Depending on dominant components, the dust solution can be neutral, acidic or basic. Chrazn reported that industrial dusts form a mixture of many chemical substances, only partly soluble in water. The conductivity of dust increases with the content of the soluble components and thus is an important factor in assessing the insulation contamination hazard. He was also of the opinion that the use of ESDD as a parameter of contamination hazard should be limited to dusts containing only strongly soluble components, thus significantly limiting use of ESDD.

K. Naito et al, 1988[88] studied the effect of the soluble materials and effect of non-uniform contamination. It was found that for inland areas gypsum ($CaSO_4$) and little NaCl are the usual contaminants. The withstand voltage for gypsum is much higher as its solubility is lower. It was found that V_{50} was higher by 15% with mixed soluble material suggesting that a fewer number of units in a string can be used in an inland area as opposed to a seaside area even for same ESDD level.

A joint task force of IEEE and CIGRE' [40] working group studied the reasons for dispersion of result in earlier report **[82]** regarding clean fog test. The task force found that differences in procedure of wetting, coating, and voltage application were primary reason for the dispersion. The group suggested that clean fog test procedure is suitable for adoption as standard test. The group concluded that repeatable, reproducible results can be obtained by using model specification as given in appendix A **[40].**

Khalifa et al, 1988[19] developed a new monitor for pollution on AC line insulators. The insulators were artificially polluted in the high voltage laboratory under simulated conditions. The solid layer method was used for artificially polluting the insulator. Use of cement, gypsum, lime was tried for replacement of Kieselguhr **[89]** and was found that lime powder may simulate Egyptian desert pollution **[90], [91].** NaCl, $CaSO_4$, KCl and lime were used in different proportion **[19]** to represent artificial contaminant, combination of all the salts as per their relative weights reproduced the

natural desert contaminant. Water was added in small steps from 10 to 1000 ml to simulate atmospheric conditions starting from slight condensation in misty air, drizzle and heavy rain contrary to use of full 1000 ml water as specified by **IEC [89].** It was observed that artificially polluted insulators do allow flashover at voltages lower than those naturally polluted for same conductivity and environmental condition. The test procedure was to suspend the polluted insulator of certain conductivity inside a fog chamber with relative humidity of 100% and alternating voltage was increase till flashover occurred. The surface leakage current built up to hundreds of milliamperes and due to heating, dry bands were formed leading to partial arcs and bursts of leakage current. The developed monitor comprised of a transmitter and a receiver/controller. If the leakage current amplitude exceeded a preset level, numbers of bursts were counted and if it exceeded critical value, the monitor judged it and sent alarm signal to service crew for cleaning insulators before flashover occurred and supply failed.

P.J. Lambeth, 1988[92] proposed a stepwise voltage application that gives numerous flashovers in a single test for the clean fog method, similar to that of salt fog method. This technique reduced the testing time and cost as compared to constant voltage artificial pollution test.

C. Lozano-Sousa, et al, 1990[93], studied the patterns of pollution on insulators in Mexico by clustering of seasonal variation and exposure period. ESDD was used as indicator of the pollution value and after analysis of field data clustering of test sites with well defined patterns of behavior considering seasonal variation was obtained. This experimentation procedure was found to be useful for designing future transmission and distribution installations in polluted conditions.

Naito et al, 1990[11] investigated the insulation performance of insulator covered with lichen (plant group consisting of fungi and algae) on specimen insulators from Paraguay, Mexico and New Zealand. Flashover voltage test, ESDD measurement, chemical analysis, physical analysis and

biological analysis of contaminants were done. It was concluded that fungi and algae on their own did not cause much reduction in withstand voltage but flashover could be only caused if the biological growth was thick and there was superposition of salt.

A. Rumeli and Suleiman Al-Debeiky, 1990 [94], presented a study on pollution flashover performance of high voltage insulators around Jeddah region. They conducted tests on cap and pin, long rod insulators by exposing them to natural pollution at four locations in Saudi Arabia. The exposure period was 100 days, 1 year and 2 years. They reported the withstand characteristics of insulators used for 110 kV line; suggesting 15% higher withstand characteristics of cap-pin type insulator than long rod type. It was also reported that 10 disc of cap and pin type provides a better pollution flashover performance than the long rod type having the same height.

M. Akbar and F.Zedan, 1991[95] studied the performance of high voltage transmission line insulators in desert conditions. The study was prompted as experience revealed that contamination related outages were adversely affecting the reliability of electrical power supply in eastern and western regions of Saudi Arabia. The performance of different insulators was evaluated for about 30 months through the measurement of ESDD, highest value of current (I-highest), surge frequencies and number of flashovers. The chemical analyses of the contaminants led to the conclusion that sodium salts followed by calcium salts were dominant soluble salts whereas silica was the major insoluble contaminant. Zedan et al modified the pollution severity range as given in Table III-1 **[17].** The modified pollution severity as given by Akbar and Zedan is given in Table 1.4. Since the test area was located near the coast (RH~80%) most flashover occurred during late evening or early morning. They were of the opinion that I-highest data could be used to signal the need for maintenance of transmission lines. Use of dust deposit gauge could give reasonable site severity level.

Table 1.4

ESDD (mg/cm^2)	Site Severity
0 – 0.03	Very light
0.03 – 0.06	Light
0.06 – 0.10	Medium
0.10 – 0.30	Heavy
0.30 – 0.50	Severe
0.50 – 1.0	Extremely Severe

Lin Xiaonan et al, 1991[20] and X.Lin et al, 1992[21] conducted insulator contamination test on various insulators at two sites, a steel plant and a substation in china. The ESDD/NSDD was measured periodically under de-energized condition and values over $1mg/cm^2$ and $5gm/cm^2$ were obtained. The chemical analysis revealed that Bassanite ($CaSO_4.1/2H_2O$) which is product of industrial smoke and soot from chemical plants and/or steel plant was the dominant contaminant (about 80%) in both the areas. Non soluble material such as SiO_2, Fe_2O_3, CaO, MgO and K_2O were also present. SiO_2, Fe_2O_3, CaO, were the dominant non soluble contaminant. Naturally contaminated insulator were tested for withstand voltage in artificial fog. Clean fogs withstand voltage tests were conducted on artificially contaminated insulator simulating the constitution of actual contaminants. Drastic reduction in withstand voltage was obtained when small amount of NaCl was included in the contaminants.

G. Ramos, et al, 1993[12][96] studied the characteristics of various conductive contaminants that pollute high voltage insulator. The observed difference in performance of the naturally and artificially contaminated insulator even with same ESDD could be attributed to the solubility of the materials. Temperature has a significant influence on the contamination flashover voltage. The influence of time, temperature on conductivity was also studied. Measurement of pH was also made and was concluded that the

contaminants were almost neutral and the solution would not damage the insulator surface.

W.A. Chisholm et al, 1994 [97], suggested that accurate estimates of low levels of insulator contamination (~0.2mg/cm^2) can be obtained only if conventional surface contamination measurements are corrected. The rag-wipe technique was outlined and expression for ESDD calculation was given as

$$ESDD = \sigma V/\sigma_{eq}A$$

Chisholm listed the measurement error sources as

(i) The insulator might have some initial contamination level. Washing insulator by de- ionized water leads to initial ESDD below 10mg/ cm^2

(ii) The wash water conductivity may also introduce error and so the equation given below is used

$$ESDD = (\sigma_{final} - \sigma_{initial})V/ \sigma_{eq} A$$

(iii) The container in which the contaminant is collected must be conditioned.

(iv) Instrument errors might also creep in

In addition to the above errors the equivalent NaCl conductance is not constant but depends on the concentration. The temperature coefficient to correct NaCl solution is different from those of other ions. The following equation was recommended for use

$$ESDD = \frac{0.42V}{A}\left[\frac{\sigma}{1+C_t(T_w - 20^0 C}\right]^{1.039}$$

J.G. Wankowicz and Z.Pohl, 1995 [98], studied and reported the influence of insulator position on flashover voltage. They found that pollution flashover voltage for thick layer contaminated insulator is higher by 20 -30 % for the horizontal position. This was attributed to the fact that horizontal position insulators have better self cleaning capability.

W.A. Chisholm et al of Ontario Hydro Technologies, **1996 [99]** were of the opinion that electrical performance of outdoor insulation degrades

severely during combinations of factor that include surface contaminants, ice, fog and an ambient temperature that rises to 0^0C. Ontario hydro found that winter fog conditions are particularly severe for contamination related insulator flashovers because under freezing conditions, fog and light ice accretions will stabilize surface pollution in layer of ice and when this ice melts, efficient surface wetting occurs. Contamination severity was classified as light(2-30μg/cm^2), moderate (30-60μg/cm^2), (60-200μg/cm^2), (>200μg/cm^2).It was found that quasi water layer at ice-air interface(0.2mm) could be more dangerous than ice layer of 2mm. It was found that the flashover voltage decreased as temperature increased from – 3^0C to 0^0C for different ESDD.

Matsuoka et al, 1996[100] compared the basic contamination withstand voltage characteristics of polymer insulators with those of porcelain insulators. A new contamination method, different from that used for ceramic insulators was developed for polymer insulator. It was found that contamination withstand voltage of silicone rubber insulator is more influenced by fog density than porcelain insulators. The dependence of withstand voltage on SDD was similar as for porcelain (WSV α SDD$^{-0.2}$)**[96]**.

Richards and Renowden, 1997 [101] developed a remote control monitor to monitor contamination. Three methods of monitoring viz. leakage current, weather parameters and liquid water sensor (LWS) were used. It was shown that leakage current monitoring is an unreliable indicator of contamination level except near pre-flashover levels. LWS was shown to be a surrogate indicator of the build-up of contamination on insulators. Empirical relations that related wind speed and concentration and deposition of insulator contamination could be used as a powerful indirect method of determining the levels of contamination.

IEEE working group on insulator contamination, 2001[102], suggested that measurement of surface resistance of insulators under wet

conditions could provide valuable information on several aspects of insulator performance. The group recommended guidelines for surface resistance measurement of non-ceramic insulators.

S.M. Gubanski, et al, 2001 [22], studied the effects of biological contamination on insulator performance. The problem is acute in Sri Lanka, Tanzania and so insulator with fungi, algae, lichen growth were studied and tested for wet flashover. Silicone rubber, porcelain insulators with above contaminants were tested in high voltage laboratory and were found that there was large reduction in flashover voltage under wet condition. It was also observed that though there was large reduction in wet flashover voltage there had not been any flashover of algae contaminated insulator in Tanzania. This could be attributed to growth of algae in clean environment and hence risk of insulator flashover is not so strong in field condition.

Ying Long et al, 2002 [103], reported a study conducted in China during March 1993 to 1995 to determine the distribution of contamination and its severity on the surface of porcelain insulation. They were of the opinion that traditional method of ESDD calculation has limited use owing to large variation for the same ESDD and different composition of pollutant. They described the pollution level on the surface by partial surface conductivity (PSC). They related PSC and flashover voltage for both artificial and natural pollution. The maximum value for PSC was 40μS occurring during spring/winter. Relation between ESDD and PSC has also been reported in this study.

M. Abdul Salam et al, 2002 [104], proposed a mathematical relationship based on dimensional analysis. They related insulator resistance, leakage distance and ESDD. They obtained that the experimental results were in close agreement as obtained from the proposed relationship.

K.L. Chrazn, 2003 [11] presented a report on his twenty year research at Glasgow pollution test station on outdoor insulation. Leakage current and flashover voltages were recorded. A simple impulse counter was

used to measure the current. ESDD and dust deposit density was also used as pollution severity indicator. It was concluded that impulse counter can be used as a cheap tool for evaluation of pollution severity, suggesting that a value of 50mA can be recognized a warning level and countermeasures should be undertaken once the value exceeds 50 mA.

Reddy, et al, 2003[105], studied the flashover voltage across gaps on insulator top surfaces and gaps between sheds on the underside of an insulator. They also studied flashover on single and three unit insulator strings. Resistance measurement of individual units of a polluted three unit string before and after flashover indicate that strongly differing resistance of the units could be cause of flashover of ceramic disc insulator string.

Chris. S. Engelbrecht, et al, 2003[106], proposed a new method named dry salt method (DSL) as an alternative to verify the pollution flashover performance of insulators to be installed in coastal environment. In the DSL method, the ability of an insulator to withstand for a short time a specific environment at its operating voltage was determined. The DSL comprises of a separate pollution deposit and wetting phase. For the duration of the test i.e. during both the deposit and wetting phase, the insulator was energized to a specified test voltage. The parameters recorded during the test included flashover or withstand pollution level, leakage current and hydrophobicity.

Gouda, et al, 2004[107] conducted experimental study to simulate the natural pollution conditions of high voltage polluted insulators. The degree of severity was evaluated by surface layer conductivity, effect of leakage current, effect of wetting method on leakage current. Desert conditions were simulated and high voltage test were conducted when dew was usually formed due to drop in air temperature while humidity is high.

G. Montaya, et al, 2004[108] were of the opinion that maintenance of distribution networks is more effective if the insulation contamination levels are known and thus the measuring methods of pollution level are

important. Laboratory tests were conducted to reproduce pollution levels in field and were found that the quantity of non-soluble materials deposited on insulator surface affected the magnitude of leakage current. The curve between magnitude of leakage current and ESDD for a particular NSDD was almost linear.

R. Boudissa et al, 2005 [109] were of the opinion that in spite of extensive investigations done on pollution performance of outdoor insulators, flashover characteristics and its interaction with insulator shape has not been dealt with. They reported experimental findings that allowed quantifying the effects of insulator geometry on flashover voltage.

M. Farzaneh et al, 2006[110] reported the effect of the diameter of an insulator covered with ice on its flashover voltage. The insulator diameter was varied by simulating artificial ice and V_{50} was experimentally determined using IEC 60507**[89].** The results were indicative that V_{50} decreased as thickness of ice layer increased. They also proposed a mathematical model for predicting the critical flashover voltage and validated their experimental results with the proposed model.

K.L. Chrzan and F.Moro, 2007[5] studied the electrical discharges and dry band formation during pollution test in laboratory and also under natural condition. They concluded that discharges and dry bands under natural conditions can concentrate in relatively small regions leading to very nonlinear voltage distribution along the leakage path.

K.L. Chrzan, 2007 [10], reported a study on environmental conditions in West Europe, Poland and Algeria on outdoor insulators performance and selection. It was reported that continuous assessment of pollution condition should be assessed for judicious selection of insulation level. Since the environmental condition in Europe has improved considerably, the insulation level to be used for new installation should conform to IEC publication 60815 and not to what was say 20 years back.

Owing to salt sands and dust storms in the desert areas, very long specific leakage distances have to be applied.

L.S. Patras et al, 2007 [111] reported a study that used ESDD and NSDD values for mapping the pollution level at four different locations of Minhasa Electrical Distribution System in Indonesia. This mapping can be used to determine the outdoor insulation level, insulation design and also to predict the time interval for washing period of insulators.

Asfar A. Khan et al, 2007 [112] [113] studied the effect of pH and conductivity on artificially polluted porcelain disc insulators. Artificial contaminants such as NaCl, KCl, CaO were used. The difference in the FOV was attributed to increase in hydroxyl ions for different salts.

Fueng Zhang et al, 2008[114] studied the flashover performance of porcelain insulators in high altitude areas. They studied the effect of non-soluble deposit and different salts on insulator performance. They found that non-uniformly contaminated insulators have higher $U_{50\%}$ than uniformly contaminated insulator. It was also reported that $U_{50\%}$ increased with increasing percentage of lowly soluble $CaSO_4$. Zhang et al also concluded that $U_{50\%}$ decreased with NSDD.

Asfar A. Khan et al, 2008[115] reported a study conducted on artificially polluted porcelain disc insulators under conditions of natural fog. The study was conducted during winter month at Aligarh. Asfar et al reported that pH of the pollutant in addition to conductivity can be used as an effective pollution severity indicator. NaCl, KCl, $MgSO_4$ and CaO were used as the artificial contaminants. The study attributed the difference in the fall of flashover voltage on the difference in the ionic size of the ions. It was also reported that addition of CaO to NaCl resulted into increase of flashover characteristics; this is similar to what was reported by Zhang **[114]**

Asfar A. Khan et al, 2009 [116], in their study on effect of pH and fog on naturally polluted insulators reported that the locational pollutants decide the flashover characteristics of an insulator. It has been reported that as the pH

of deposits becomes more acidic i.e. pH changes from 7 towards 0, there is drop in FOVUID values. It has been suggested that pH monitoring be used as a Diagnostic tool for devising a maintenance schedule as soon as pH of prevalent contaminant exceeds a predetermined value.

1.7 Summary of literature review

From the above review it is noted that tremendous pace has been achieved in the expansion of electrical power transmission system since the advent of electricity in 1880's. Although great advancements in electrical technology has taken place in the last century but porcelain has remained as the main electrical insulator in large part of the world even today. Nonetheless the shape and size of porcelain insulators that are extensively used in majority of countries has seen considerable modifications. It is clear that for the proper understanding and design of insulators for different environmental conditions, it is necessary that extensive studies be undertaken. There have been number of studies in the last hundred years on ceramic as well as non-ceramic insulators. Almost all the studies revolve around electrical parameters such as flashover voltage, withstand voltage, leakage current, conductivity, chemical analysis of pollutants and salt deposit density. No doubt the parameters of interest have remained the same, but the methodology involved in studying and understanding differed. Some researchers performed their study under natural conditions and others under artificial or simulated conditions. The studies under natural conditions have marked advantages and disadvantages. Keeping in view the rate at which power transmission system is growing, depending solely on natural method of testing will hamper the growth of insulation and its application technology. Therefore, testing insulators with artificial methods that approximates natural conditions have gained prominence. Since evaluation of pollution severity is a complex problem, use of above testing methodology should be used for identification of new severity indicators apart from the existing indicators.

Chapter-2

Statement of the Problem

2.1 Statement of the Problem

The use of insulators in electrical network dates back to the advent of electricity in 1880's. The material that was thought to be eminently suitable for permanent exposed insulation was porcelain due to its property of being non-hygroscopic, non-inflammable and non-reactive to chemical substances. The earliest prototype of the modern high tension insulator was a petticoat insulator of the same cylindrical form as the low voltage telegraph insulator, but somewhat larger. With time, by 1897, the shape of the insulators changed with the spreading of the outer sheds giving it shape of an umbrella and reducing brush discharges and flashovers **[42].** Since the earliest days of power transmission, contamination flashover has plagued overhead transmission lines. Flashover triggered by early morning dew deposits were noted as early as in 1902. Systematic research into the causes of contamination flashover appears to have begun with Anfossi's study in 1907. The modification in the design of insulator is a continuous process and has continued during last 100 years to suit different conditions and reduce chances of failure.

The successful, reliable and uninterrupted operation of power system depends to great extent on reliable insulation. Thus insulation must not deteriorate so as to lead to line outages **[70].** Transmission lines pass through areas that are different in not only topography, terrain and environmental conditions. The deterioration in the insulating property of porcelain insulator depends on the surrounding conditions en route of the installed transmission lines. In service insulators have number of pollutants that deposit on their surface, these deposits, if dry, are not a potential threat to the insulating capabilities. On the other hand if these deposits are wet, since water is itself an important pollutant, the insulating properties are greatly reduced **[6].** Thus for proper uninterrupted operation of a power system, it is necessary that insulators remain healthy and give the desired level of performance.

For the proper understanding and design of insulators for different environmental conditions, it is necessary that extensive studies be undertaken. There have been number of studies in the last hundred years on ceramic as well as non-ceramic insulators. Almost all the studies revolve around electrical parameters such as flashover voltage, withstand voltage, leakage current, conductivity, chemical analysis of pollutants and salt deposit density. No doubt the parameters of interest have remained the same, but the methodology involved in studying and understanding has differed. Some researchers performed their study under natural conditions and others under artificial or simulated conditions. The studies under natural conditions have marked advantages and disadvantages **[74].** Keeping in view the rate at which power transmission system is growing, depending solely on natural method of testing will hamper the growth of insulation and its application technology. Therefore, artificial methods of testing have gained prominence.

Literature survey in the foregoing chapter suggests that experiments are designed and carried to understand the performance of the insulators under conditions of different type of pollution. The present study addresses this problem by making efforts to relate the electrical parameters such as withstand voltage, flashover voltage to chemical parameters such as pH, conductivity, ESDD, ionic radii, degree of hydration of ions, solubility, transportation number, activity coefficient of ions atomic and molecular mass of prevalent pollutants.

2.2 Work Plan

To achieve the above, set of experiments as detailed below were designed and carried out. The work was divided to be carried under natural and artificial conditions of pollution.

2.2.1 Natural Condition Testing

For natural condition testing and monitoring condition of the porcelain insulator, the test samples were placed at different locations in and around Aligarh (India). Aligarh lies in subtropical climatic zone and is

located at 27.88°N latitude and 78.08°E longitude at height of 178m above mean sea level. The city has hot and dry summer with mean temperature between 32.2-33.8°C; the mean winter temperature ranges between 12.2-15.0°C. Aligarh has intermittent rainy season with an annual average rainfall of around 850mm.

In order to carry out the investigation, three typical locations representing a road highway, an area near thermal plant and a residential area have been selected. The description of the locations and the related probable types of pollution are given in Table 2.1

Table 2.1

Location/Site	Description of the location
1	A site outside of the city at an electrical substation at Sarsaul on national highway (NH 91) that connects Kanpur to Delhi with a very heavy traffic (vehicular pollution, dust, agricultural pollution)
2	A site very near to a coal fired thermal power plant at Kasimpur ,Harduaganj, Aligarh (Fly ash, dust, agricultural pollution, low vehicular traffic)
3	A residential area at Nishat Apartments, Aligarh (no industry nearby , very low vehicular traffic)

The cap and pin type of insulator have been chosen for the test. The selected porcelain insulators have been exposed to various types and intensities of pollution at the selected sites for different duration. The study period was about 30 months.

The investigation was initiated by installing the cap and pin type insulator under unenergized state in each of the three selected regions in first week of July 2005. The test insulators were positioned at almost the same height of the line insulators, without voltage being applied, and were left to natural pollution. The samples were periodically removed from the site in December 2005, March 2006, July 2006, December 2006, December 2007,

March 2008 for testing. The tests were conducted at an interval of 4 months. One sample set was also tested after exposure period of one year. The samples at the end of the desired exposure period were brought to the high voltage laboratory of Electrical Engineering Department of Aligarh Muslim University, Aligarh for measuring the desired parameters.

2.2.2 Artificial Condition Testing

Based upon extensive literature review and also on the basis of occurrence of salts in nature as given in section 3.2, artificial pollution test with the salts and their combination were undertaken. A number of salts and their combination were taken as contaminant because the evaluation of insulator performance could only be partially established using one kind of contaminating slurry. A more complete evaluation would require tests with several kinds of slurries. The artificially contaminated insulators were exposed to natural condition of wetting (dew, fog, drizzle). Thus a condition that was semi-natural was simulated. It is being coined as a semi-natural testing methodology because two pollutant are being taken, one the solid salt and the other water (moisture). Water is also a pollutant, without which almost no flashover would occur. The solid pollutant is artificial (salt) whereas water is due to natural reasons and thus semi-natural testing may be an apt word for the used testing method.

(i) Experiments Using Single Salt

The experiments using single soluble salts are as detailed below:

1. Sodium Chloride (NaCl) as contaminant.
2. Potassium Chloride (KCl) as contaminant.
3. Calcium Chloride ($CaCl_2$) as contaminant.
4. Calcium Sulphate ($CaSO_4$) as contaminant.
5. Sodium Sulphate (Na_2SO_4) as contaminant.
6. Magnesium Sulphate ($MgSO_4$) as contaminant.
7. Sodium Nitrate ($NaNO_3$) as contaminant.
8. Calcium Nitrate $Ca(NO_3)_2$ as contaminant.
9. Magnesium Nitrate $Mg(NO_3)_2$ as contaminant

(ii) Experiments Using Multi Salts

Experiments were also designed with combination of soluble salts and a non soluble salt, Calcium Oxide (CaO)

1. $NaCl + CaSO_4$ as contaminant
2. $KCl + CaSO_4$ as contaminant
3. $NaCl + CaO$ as contaminant
4. $KCl + CaO$ as contaminant
5. $CaSO_4 + CaO$ as contaminant
6. $Mg(NO_3)_2 + CaO$ as contaminant

After conducting the experiments detailed analysis of the result was carried out to correlate

I. Withstand Voltage with Conductivity and ESDD

II. Flashover Voltage with Conductivity and ESDD

III Flashover Voltage with pH

The characteristics obtained above has been explained on the basis of ionic radii, hydrated radii, degree of hydration of ions, solubility, transportation number, activity coefficient of ions atomic and molecular mass of pollutants and the presence of hydrogen ion and hydroxyl ion. Based on extensive experimentation, both with natural and artificial pollutants the conclusions drawn are as given under:

1) For a fair and judicious insulation design/level, accurate knowledge of locational pollutants is important. Thus insulation requirement must be tailored fit for every location.
2) Detailed qualitative chemical analysis of pollutants in the area surrounding Aligarh lead to presence of Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, CO_3^{2-}, Cl^-, NO_3^{2-} and SO_4^{2-} (in dust and ground water), Cd, Cr, Pb, Fe, Cu, Ni, Zn, Mn (in soil due to ground water characteristics), fly ash and oxides of sulphur and nitrogen (due to thermal plant, brick kilns), particulates, CO, oxides of sulphur and

nitrogen (due to vehicular emissions) , phosphate and nitrates (due to agricultural fertilizers)

3) Insoluble component of deposits does not directly contribute to conductivity but aids in impediment of ionic movement, thereby leakage current.
4) The pH of the deposit and solvent affects the flashover characteristics.
5) Temperature, high RH affects withstand and flashover characteristics. Pressure in the present study remained almost constant in the range 742-745 mm of Hg.
6) Temperature affects viscosity of electrolytic solution and thus has an effect on withstand and flashover characteristics.
7) Higher RH leads to increase in availability of dissociated water molecules, thus affecting withstand and flashover characteristics.
8) Deposits with univalent cations have higher speed of movement (due to smaller ionic cloud density) than bivalent cations.
9) Ionic and hydrated radii affects withstand and flashover characteristics.
10) Solubility of salt also plays major role in deciding the withstand and flashover characteristics.
11) Transportation number affects leakage current flow.
12) For multi contaminant deposit, interaction of multi cation/ anion decides behaviour of insulation.
13) Activity coefficient of ions is also responsible for change in withstand and flashover characteristics due to addition of sparingly soluble/insoluble salt.
14) The flashover characteristics obtained after extensive experimentation with various soluble and insoluble salts leads to proposition of a model that can be used for semi-arid/sub-tropical climatic zone such as Aligarh.

Chapter-3

Experimental Set-up

3.1 Introduction

In the present work disc type porcelain insulators have been tested under natural and artificial conditions simulating different pollution conditions. Tests under natural conditions have been conducted on three locations such as highway, industrial (thermal power plant) and clean residential area.

The test were carried out using the cap and pin type insulators which are extensively used in overhead networks in India and neighboring countries. The unit diameter is 254 mm, its spacing is 146 mm, and its total leakage distance is 305 mm. The total surface area is 1599 mm^2. A number of disc insulators were arranged on loan from author's sources in UP Power Corporation Limited.

3.2 Choice of salts

Extensive literature search regarding the chemical analysis of contaminants found on insulators in different conditions of pollution led to the conclusion that the predominant soluble salts are $CaSO_4$, $NaNO_3$, $Ca(NO_3)_2$,NaCl, KCl, Na_2SO_4, $NaNO_3$,$MgCl_2$, $Mg(NO_3)_2$, $MgSO_4$, $CaCl_2$. The insoluble salts found were SiO_2, Fe_2O_3, CaO, MgO and K_2O.

3.2.1 Salts used in present study

In the present work tests were focused on measurements with soluble salts such as NaCl, KCl, $CaCl_2$, $MgSO_4$, $CaSO_4$, Na_2SO_4 ,$NaNO_3$,$Mg(NO_3)_2$ and $Ca(NO_3)_2$ .The insoluble salt that was used in this work is CaO.

3.3 Sample Preparation

The porcelain insulators that are extensively used on transmission lines in India have been used for testing in the present work. Before testing, insulators were treated to make them suitable for testing.

3.3.1 Pretreatment

Prior to preparation of the sample for testing, pretreatment of the specimen is necessary. The surface of the specimen insulators were cleaned and were washed with detergent to remove repellency, the sample was dried after washing **[8]**.

3.3.2 Contamination Procedure

The pre treated insulators were thoroughly contaminated with contaminants as given in section 3.2 using the dipping technique **[8]** in salt solution of specific contaminant and expected salt deposit density. After dipping the insulators for about 2 hours they were left in sunlight to dry. The slurries were prepared using single soluble salts and with multi salts.

(i) Single soluble salt slurries

The contaminating slurry was prepared using NaCl, KCl, $CaCl_2$, $MgSO_4$, $CaSO_4$, Na_2SO_4 ,$NaNO_3$, $Mg(NO_3)_2$ and $Ca(NO_3)_2$ .The insoluble salt that was used in this work is CaO listed in section 3.1.1. Known quantity of soluble salt was mixed in water to get desired the ESDD.

(ii) Multi salt slurries

The contaminating slurry was prepared using combination of soluble salts listed in section 3.2.1 with CaO. Known quantity of soluble salt was mixed in water to get different salt concentration slurry. The slurry was prepared using multi salts in water. The multi salt slurries used consisted of the following:

1. NaCl + $CaSO_4$ as contaminant
2. KCl + $CaSO_4$ as contaminant
3. NaCl + CaO as contaminant
4. KCl + CaO as contaminant
5. $CaSO_4$ + CaO as contaminant
6. $Mg(NO_3)_2$ + CaO as contaminant

3.4 Parameters to be recorded

The parameters that were identified to be useful for undertaking the present study were flashover voltage, withstand voltage, conductivity, pH, and ESDD.

3.4.1 Weather conditions

Since most of the parameters to be recorded were strongly dependent on weather as the variation in barometric pressure and humidity of atmosphere causes variation in the electric strength of the air and also in the performance of insulators exposed to air, proper record of temperature, pressure, humidity was necessary for obtaining proper conclusions in the study.

3.5 Measurement System

In the present work measurement system for measuring voltage, conductivity, pH, pressure, temperature, humidity are required. The description of the various measurement systems used is given in the following sections.

3.5.1 Supply and Measurement of High Voltage

The results of artificial pollution test are affected by testing transformer and power source as well as testing method. The power sources used for making contamination tests should have sufficient short circuit current available to prevent a voltage dip when flashover is imminent. It has been found that with a small amount of pollution a source of 5A is sufficient, but that as the contamination increased 10A or more is necessary **[8].**

The high voltages were obtained from a testing transformer (Fig.3.2, Fig.3.3) of 0.391/150 kV, 50 Hz, 1-phase, 30 kVA rating. The voltages were measured using a voltmeter (accuracy ± 3%) connected to the primary side of the transformer, that reads the low side voltage. The corresponding high

voltages are obtained from a calibration curve (Appendix A-3) drawn by using the sphere – sphere electrode system having diameter of 25 cm **[117] [118].** The circuit arrangement is shown in figure 3.1. Photographs showing high voltage testing transformer and control panel are given in figure 3.2 and 3.3.

3.5.2 Conductivity Measurement system

The conductivity of the contaminant deposited on the surface of the insulator was measured using CM 180 conductivity meter, having cell constant 0.1 to 1 and conductance range from 20 μS to 200 mS. The least count of the meter was 0.01 μS. The photograph of the conductivity meter used for measurement is given in figure 3.4.

The deposited salt was removed using paint brush or dry scrapping. Solution of this scrap was made in a solution of 1000ml of distilled water. The meter was calibrated in the desired range. The meter electrode was dipped enough in the beaker containing the sample solution and reading was recorded.

3.5.3 pH Measurement system

The pH value of the contaminant was measured after removing deposited contaminant on the sample using LI 120 pH meter with range from 0-14. The least count of the pH meter was 0.01. The photograph of the pH meter used for measurement is given in figure 3.5.

The deposited salt was removed using paint brush or dry scrapping. Solution of this scrap was made in a solution of 100ml of distilled water. Calibration of pH meter was done with the help of buffer solutions of pH 4 using potassium hydrogen phthalate and pH 9.2 with sodium hydrogen carbonate. After calibration of the pH meter, the pH electrode was dipped in the sample solution for few seconds. The pH value of the sample solution was recorded after the meter reading settles to a fixed value.

3.5.4 Pressure and Temperature Measurement system

The pressure was measured with the help of a barometer. The accuracy of pressure measurement was ±0.50 Torr. Wet and dry bulb thermometers were used to record the temperature in the laboratory. The measurement could be made with an accuracy of ±0.2 degree centigrade.

3.5.5 Humidity measurement system

The absolute humidity measurement was done using the wet and dry bulb temperature readings and the curve given in Figure 10.1**[116]** (Appendix A-5). The absolute humidity obtained from the above curve was converted into relative humidity (RH) using the conversion table **[117].**

3.6 Test Procedure

The test procedure involved pretreatment of insulators, contamination by exposure to natural conditions of pollution at the sites detailed in Table 2.1. Figures 3.6 and 3.7 show insulators at location 2. For testing under artificial condition different slurries of contaminants (salts) as given in section 3.3.2 were used for contamination. Figures 3.8 and 3.9 show an artificially contaminated insulator. After the desired level of exposure to conditions of pollution and wetting was achieved, withstand voltage tests and flashover voltage tests were conducted as detailed in the next section.

Arrangement of Insulators

The suspension insulator, complete with its metal parts and accessories as in service, was suspended vertically from an earthed metal cross-arm whose length was at least 1.5 times that of the insulator. No other earthed object was near to the insulator (as per IS 731-1963) **[121].** A conductor with diameter of 10 mm was connected to the clamp of the insulator and connected to ground.

3.6.1 Withstand test

In this test, the voltage specified in the relevant specification (IS 731-1963) applied under dry or wet conditions for one minute with an insulator mounted as in service conditions. The test piece should withstand the specified voltage **[121].** The withstand voltage per unit insulation distance (WSVUID) was obtained by dividing the withstand voltage by the leakage distance available and the values are presented in tables 4.1-4.42.

3.6.2 Flashover Test

(i) Dry power frequency flashover voltage test

To measure the dry power frequency flashover voltage of the specimen insulator, the voltage from 50 Hz HV testing transformer was applied across the insulator and raised till flashover occurred. The voltage was read from the low voltage side voltmeter and converted to its high voltage side value with the help of calibration curve (Appendix A-3). Tables 4.1- 4.42 provide flashover voltage per insulation distance (FOVUID) for a particular contamination and ESDD. Each observation is the mean of flashover voltages of five to six readings.

(ii) Wet Flashover Voltage test

The insulator unit with the contaminants was left overnight in the open atmosphere to be wetted by fog and dew (Natural Wetting). To measure the wet power frequency flashover voltage of the specimen insulator, the voltage from 50 Hz HV testing transformer was applied across the insulator and raised till flashover occurred (Figure 3.10 shows one such flashover). Tables 4.1- 4.42 give the observed value for wet flashover tests and each observation is the mean of flashover voltages of five to six readings

The values of withstand voltages and flashover voltages in the tables 4.1- 4.42 have maximum SD of ± 0.15 and minimum of ± 0.09.

3.7 Measurement of Pollution Severity

The pollution severity can be given by the conductivity of the contaminant, pH of the contaminant, conductivity and ESDD measurement.

3.7.1 Conductivity Measurement

The procedure for measurement of conductivity is given in section 3.5.2.

3.7.2 ESDD Measurement

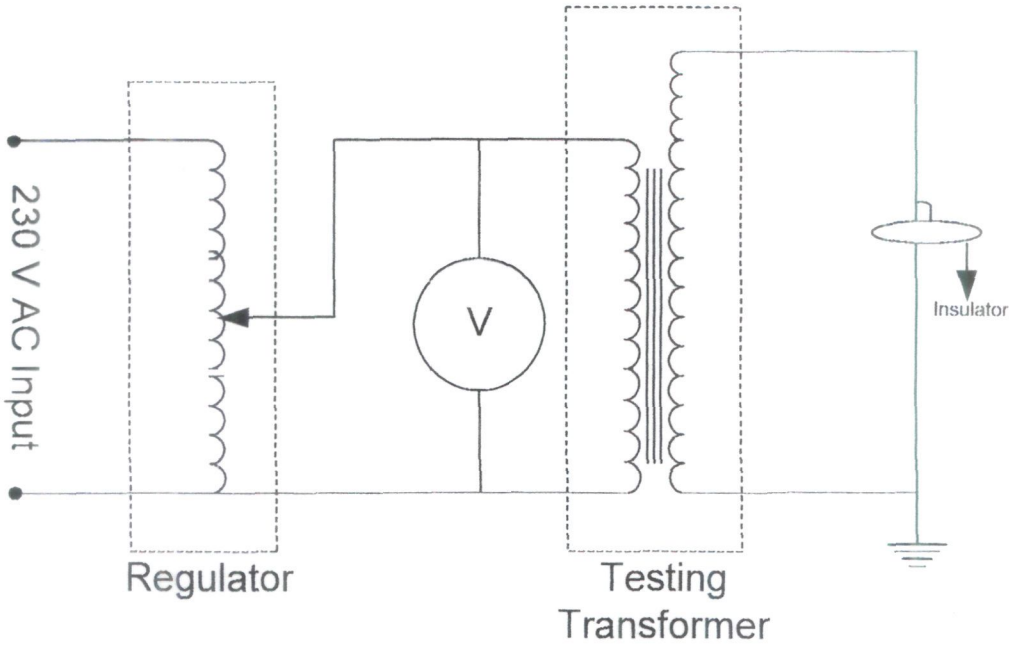
Pollution severity was measured in terms of Equivalent Salt Deposit Density (ESDD). The measurement equipment consisted of Conductivity Bridge, a thermometer and sets of individual flasks for collecting the contaminant samples. The samples were taken by removing the insulator surface deposits with paint fur brush; repeatedly the brush was rinsed with distilled water in the flasks. The conductivity of the sample solution in 60 ml of distilled water was measured with conductivity meter (as given above).

Equivalent Salt Deposit Density (ESDD) was obtained by the procedure given in appendix A-1

The concentration of the various contaminants was varied to have a different salt density. The flashover tests for the different values of ESDD were conducted Flashover voltage and withstand voltage for six to eight values of ESDD were measured and are given in table 4.1 – 4.42.

3.7.3 pH Measurement

The pH value of the contaminant was measured as per procedure given in section 3.5.3.



V-Voltmeter, Calibrated in kV

Fig. 3.1 Circuit arrangement

Fig. 3.2 Testing Transformer

Fig. 3.3 Control Panel

Fig. 3.4 CM 180 Conductivity Meter

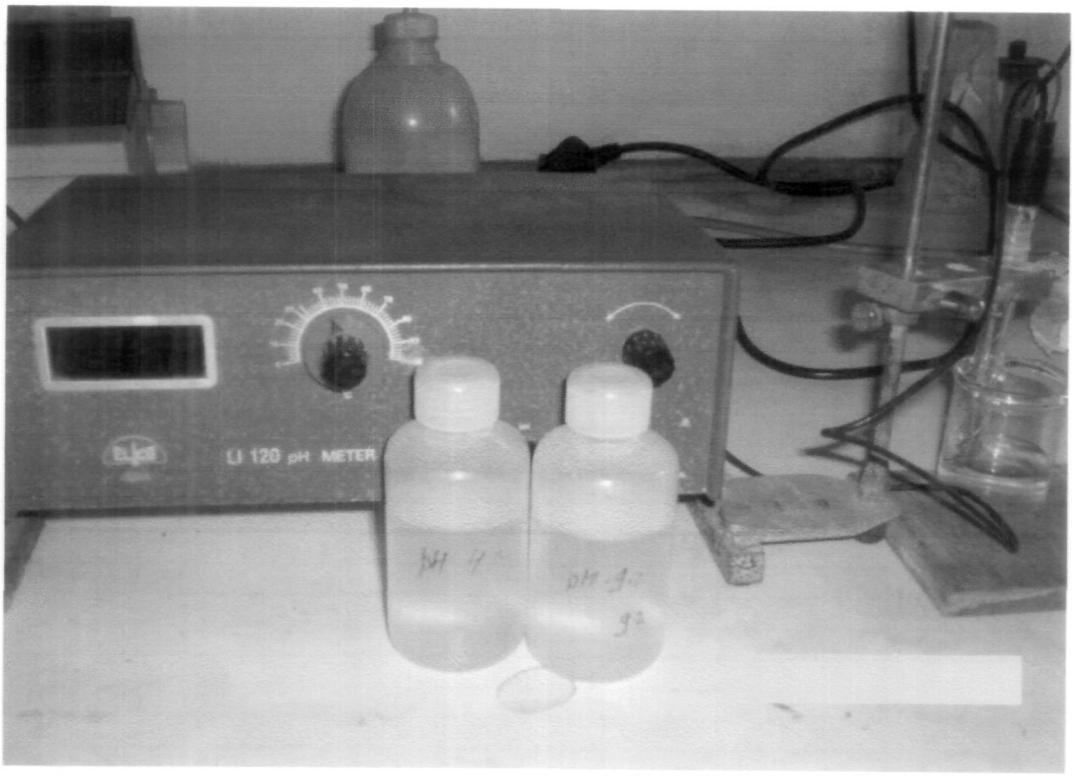


Fig. 3.5 LI 120 pH Meter

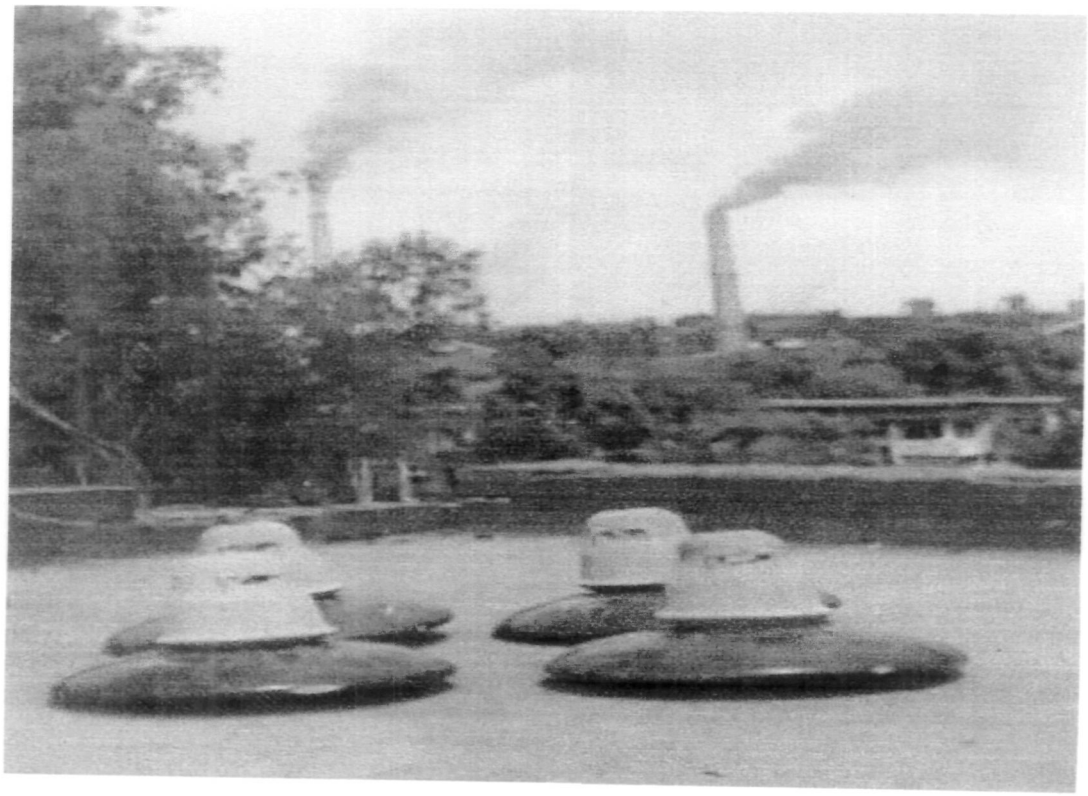


Fig. 3.6 Naturally Polluted Insulators (Location 2)

Fig. 3.7 Naturally Polluted Insulators (Location 1)

Fig. 3.8 Artificially polluted insulator (Top surface)

Fig. 3.9 Artificially polluted insulator (Bottom surface)

Fig. 3.10 Insulator Flashover

Chapter-4

Results

Results

As per the work plan detailed in chapter 2 and experimental methodology outlined in chapter 3, experiments were conducted to achieve the desired objective of this thesis. As already mentioned in previous chapters, tests under natural pollutant – natural wetting and artificial pollutant – natural wetting conditions have been performed. This chapter details with the results obtained. The measurements done were to get values of conductivity, pH, and flashover voltage, withstand voltage with proper recording of temperature, pressure and humidity. ESDD was calculated using empirical relation as given by Chisholm **[97]**. Each reading given for voltages is the mean of flashover voltages of five to six readings.

Tables 4.1 to 4.6 is the tabular representation of the data obtained for location 1 insulators.

Tables 4.7 to 4.12 is the tabular representation of the data obtained for location 2 insulators.

Tables 4.13 to 4.18 is the tabular representation of the data obtained for location 3 insulators.

Tables 4.19 to 4.20 is the tabular representation of the data obtained for insulators contaminated with NaCl.

Tables 4.21 to 4.22 is the tabular representation of the data obtained for insulators contaminated with KCl.

Tables 4.23 to 4.24 is the tabular representation of the data obtained for insulators contaminated with $CaCl_2$.

Tables 4.25 to 4.26 is the tabular representation of the data obtained for insulators contaminated with Na_2SO_4.

Tables 4.27 to 4.28 is the tabular representation of the data obtained for insulators contaminated with $MgSO_4$.

Tables 4.29 to 4.30 is the tabular representation of the data obtained for insulators contaminated with $CaSO_4$.

Tables 4.31 to 4.32 is the tabular representation of the data obtained for insulators contaminated with $NaNO_3$.

Tables 4.33 to 4.34 is the tabular representation of the data obtained for insulators contaminated with Ca $(NO_3)_2$.

Tables 4.35 to 4.36 is the tabular representation of the data obtained for insulators contaminated with Mg $(NO_3)_2$.

Table 4.37 is the tabular representation of the data obtained for insulators contaminated with double salt i.e. NaCl + $CaSO_4$.

Table 4.38 is the tabular representation of the data obtained for insulators contaminated with double salt i.e. KCl + $CaSO_4$.

Table 4.39 is the tabular representation of the data obtained for insulators contaminated with double salt i.e. NaCl + CaO.

Table 4.40 is the tabular representation of the data obtained for insulators contaminated with double salt i.e. KCl + CaO.

Table 4.41 is the tabular representation of the data obtained for insulators contaminated with double salt i.e. $CaSO_4$ + CaO.

Tables 4.42 is the tabular representation of the data obtained for insulators contaminated with Mg $(NO_3)_2$ + CaO.

Figures 4.1 – 4.18 shows graphical variation of FOVUID and WSVUID with ESDD for the three locations.

Figures 4.19 – 4.27 shows comparative graphs of FOVUID vs ESDD for different cases of naturally polluted insulators.

Figures 4.28 – 4.45 shows graphical variation of FOVUID and WSVUID with pH for the three locations.

Figures 4.46 – 4.54 shows comparative graphs of FOVUID vs pH for different cases of naturally polluted insulators.

Figures 4.55 – 4.72 shows graphical variation of FOVUID and WSVUID with ESDD for different soluble salts.

Figures 4.73 – 4.93 shows comparative graphs of FOVUID vs ESDD for different salts and different ambient conditions, for different anions and cations.

Figures 4.94 – 4.111 shows graphical variation of FOVUID and WSVUID with pH for different soluble salts.

Figures 4.112 – 4.132 shows comparative graphs of FOVUID vs pH for different salts and different ambient conditions, for different anions and cations.

Figures 4.133 – 4.138 shows bar chart depicting variation of FOVUID with percentage of soluble and percentage of non-soluble salts.

TABLE 4.1: Natural Contaminant- Natural Wetting Test, National Highway (Location 1) December 2005

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 23.8-25.2°C RH= 35-45%		*Natural Wet Condition* T = 17.4 -18.6°C RH= 40-46%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.79	129.05	0.0422	1.868	3.540	1.180	3.114
2	6.73	132.49	0.0435	1.852	3.508	1.147	3.081
3	6.66	135.66	0.0445	1.803	3.491	1.131	3.032
4	6.78	137.28	0.0460	1.786	3.459	1.098	3.000
5	6.69	138.11	0.0467	1.786	3.442	1.098	2.967
6	6.70	140.08	0.0476	1.754	3.426	1.081	2.950
7	6.74	143.04	0.0482	1.737	3.409	1.049	2.918
8	6.68	144.16	0.0486	1.737	3.393	1.049	2.885

TABLE 4.2: Natural Contaminant- Natural Wetting Test, National Highway (Location 1)March 2006

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 28.4-29.8°C RH= 25-32%		*Natural Wet Condition* T =21.6-22.4 °C RH= 28-32%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.70	131.68	0.0407	1.868	3.508	1.212	3.229
2	6.75	134.54	0.0417	1.852	3.491	1.196	3.196
3	6.78	137.64	0.0427	1.803	3.459	1.196	3.163
4	6.68	140.03	0.0433	1.786	3.442	1.196	3.114
5	6.75	142.97	0.0445	1.786	3.426	1.180	3.081
6	6.71	145.07	0.0457	1.754	3.393	1.147	3.049
7	6.64	147.78	0.0468	1.737	3.377	1.098	3.032
8	6.59	150.34	0.0474	1.737	3.360	1.098	3.000

TABLE 4.3: Natural Contaminant- Natural Wetting Test, National Highway (Location 1) July 2006

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 32.4 -34.8°C RH= 62-68%		*Natural Wet Condition* T =27.4 -28.6°C RH= 65-70%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.85	142.08	0.0389	1.803	3.459	1.212	3.065
2	6.82	146.89	0.0402	1.786	3.442	1.196	3.032
3	6.80	149.36	0.0409	1.786	3.426	1.196	3.000
4	6.75	153.47	0.0420	1.754	3.409	1.196	2.983
5	6.76	156.82	0.0431	1.737	3.393	1.180	2.950
6	6.72	161.37	0.0444	1.737	3.377	1.163	2.934
7	6.67	167.94	0.0462	1.720	3.344	1.130	2.918
8	6.62	173.47	0.0477	1.720	3.327	1.130	2.885

TABLE 4.4: Natural Contaminant- Natural Wetting Test, National Highway (Location 1) December 2006

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 23.2 – 25.0°C RH= 26 -32%		*Natural Wet Condition* T = 16.8 -18.2°C RH= 30-38%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.90	92.35	0.0304	1.803	3.426	1.147	3.114
2	6.88	96.15	0.0317	1.786	3.377	1.131	3.081
3	6.86	99.39	0.0328	1.786	3.344	1.098	3.049
4	6.81	102.27	0.0338	1.754	3.311	1.098	3.016
5	6.77	106.05	0.0351	1.737	3.278	1.081	3.000
6	6.74	107.80	0.0357	1.737	3.262	1.049	2.983
7	6.72	110.42	0.0366	1.721	3.229	1.049	2.95
8	6.67	112.15	0.0372	1.705	3.213	1.016	2.934

TABLE 4.5: Natural Contaminant- Natural Wetting Test, National Highway (Location 1) December 2007

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 23.8 - 24.2°C RH= 34-40%		*Natural Wet Condition* T = 18.2 – 19.2°C RH= 36-44%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.92	114.10	0.0374	1.934	3.655	1.229	3.114
2	6.89	117.04	0.0384	1.901	3.590	1.180	3.081
3	6.89	119.38	0.0392	1.852	3.557	1.131	3.032
4	6.85	121.73	0.0400	1.803	3.524	1.098	3.016
5	6.81	123.78	0.0407	1.786	3.475	1.081	3.000
6	6.79	126.99	0.0418	1.786	3.442	1.049	2.967
7	6.76	130.79	0.0431	1.754	3.409	1.049	2.950
8	6.72	135.47	0.0447	1.737	3.377	1.016	2.934

TABLE 4.6: Natural Contaminant- Natural Wetting Test, National Highway (Location 1) March 2008

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 31.4 -32.0°C RH= 55-60%		*Natural Wet Condition* T = 17.8 – 18.6°C RH= 74-80%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.92	140.18	0.0474	1.786	3.295	1.049	2.786
2	6.90	145.31	0.0492	1.754	3.262	1.049	2.754
3	6.85	146.44	0.0496	1.737	3.213	1.016	2.721
4	6.83	148.71	0.0504	1.737	3.196	0.983	2.672
5	6.79	150.42	0.0510	1.721	3.163	0.950	2.622
6	6.75	152.97	0.0519	1.705	3.147	0.934	2.573
7	6.73	156.66	0.0532	1.672	3.114	0.885	2.540
8	6.67	160.62	0.0546	1.639	3.098	0.852	2.508

TABLE 4.7: Natural Contaminant- Natural Wetting Test, Thermal Power Plant (Location 2) December 2005

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 24.8-26.2°C RH= 30-36%		*Natural Wet Condition* T = 18.4 -19.4°C RH= 42-48%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.82	159.69	0.0532	1.786	3.688	1.098	3.065
2	6.81	165.08	0.0551	1.786	3.655	1.098	3.032
3	6.79	168.26	0.0562	1.754	3.622	1.081	3.000
4	6.74	171.45	0.0573	1.737	3.590	1.049	2.967
5	6.71	174.30	0.0583	1.737	3.540	1.049	2.934
6	6.64	177.47	0.0594	1.721	3.508	1.016	2.901
7	6.61	180.63	0.0605	1.705	3.475	0.983	2.868
8	6.57	184.94	0.0620	1.672	3.442	0.950	2.836

TABLE 4.8: Natural Contaminant- Natural Wetting Test, Thermal Power Plant (Location 2) March 2006

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 27.4-29.2°C RH= 32-34%		*Natural Wet Condition* T =22.4 -23.8 °C RH= 28-34%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.83	189.13	0.0575	1.803	3.770	1.180	3.147
2	6.78	193.25	0.0588	1.786	3.737	1.131	3.114
3	6.76	196.72	0.0599	1.754	3.704	1.098	3.081
4	6.81	198.30	0.0604	1.737	3.672	1.081	3.049
5	6.79	201.78	0.0615	1.737	3.622	1.049	3.016
6	6.74	203.36	0.0620	1.721	3.590	1.049	3.000
7	6.69	205.88	0.0628	1.705	3.557	1.016	2.967
8	6.66	210.30	0.0642	1.672	3.540	1.000	2.934

TABLE 4.9: Natural Contaminant- Natural Wetting Test, Thermal Power Plant (Location 2) July 2006

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 32.8-34.2°C RH= 65-72%		*Natural Wet Condition* T = 27.2 -28.6°C RH= 68-76%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.79	179.51	0.0502	2.049	4.081	1.754	3.065
2	6.74	187.07	0.0524	2.016	4.032	1.737	3.032
3	6.71	189.13	0.0530	2.000	3.967	1.704	3.000
4	6.67	194.63	0.0546	1.967	3.934	1.672	2.967
5	6.61	200.46	0.0563	1.934	3.901	1.639	2.934
6	6.57	207.30	0.0583	1.901	3.868	1.606	2.901
7	6.52	210.73	0.0593	1.885	3.852	1.557	2.868
8	6.48	217.90	0.0614	1.852	3.836	1.540	2.836

TABLE 4.10: Natural Contaminant- Natural Wetting Test, Thermal Power Plant (Location 2) December 2006

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 22.8 – 24.6°C RH= 28 -36%		*Natural Wet Condition* T = 17.8 -18.8°C RH= 32-38%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.83	132.25	0.0436	2.622	4.114	1.983	3.213
2	6.77	137.21	0.0453	2.590	4.049	1.934	3.196
3	6.73	139.25	0.0460	2.557	4.016	1.901	3.180
4	6.68	139.84	0.0462	2.524	3.983	1.885	3.147
5	6.64	143.34	0.0474	2.491	3.967	1.852	3.131
6	6.59	147.11	0.0487	2.459	3.934	1.803	3.098
7	6.55	150.31	0.0498	2.426	3.901	1.754	3.065
8	6.52	154.96	0.0514	2.409	3.885	1.737	3.032

TABLE 4.11: Natural Contaminant- Natural Wetting Test, Thermal Power Plant (Location 2) December 2007

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 23.6 – 24.4°C RH= 34 – 40%		*Natural Wet Condition* T = 18.4 – 20.2°C RH= 36 – 44%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.79	173.50	0.0564	1.901	3.393	1.639	2.901
2	6.76	175.86	0.0572	1.885	3.360	1.573	2.868
3	6.72	179.41	0.0584	1.852	3.327	1.491	2.836
4	6.69	182.37	0.0594	1.803	3.295	1.426	2.803
5	6.64	184.73	0.0602	1.754	3.262	1.377	2.770
6	6.57	188.57	0.0615	1.737	3.213	1.327	2.737
7	6.53	192.71	0.0629	1.704	3.163	1.278	2.721
8	6.49	194.47	0.0635	1.672	3.147	1.245	2.721

TABLE 4.12: Natural Contaminant- Natural Wetting Test, Thermal Power Plant (Location 2) March 2008

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 31.8 - 32.2°C RH= 56-62%		*Natural Wet Condition* T = 17.8 – 19.4°C RH= 72-80%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.81	162.09	0.0532	2.147	3.459	1.426	2.639
2	6.78	165.61	0.0544	2.114	3.426	1.377	2.622
3	6.74	167.66	0.0551	2.081	3.393	1.327	2.573
4	6.69	170.30	0.0560	2.032	3.360	1.278	2.524
5	6.64	174.98	0.0576	2.000	3.327	1.245	2.475
6	6.58	176.44	0.0581	1.967	3.311	1.213	2.442
7	6.53	179.66	0.0592	1.934	3.278	1.180	2.409
8	6.47	182.28	0.0601	1.901	3.245	1.131	2.377

TABLE 4.13: Natural Contaminant- Natural Wetting Test, Nishat Apartment (Location 3) December 2005

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 23.6-25.0°C RH= 35-45%		*Natural Wet Condition* T = 17.2 -18.4°C RH= 40-46%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.93	102.68	0.0338	2.590	4.098	2.196	3.245
2	6.91	104.44	0.0344	2.557	4.065	2.147	3.213
3	6.91	108.24	0.0357	2.524	4.032	2.114	3.180
4	6.89	111.16	0.0367	2.491	4.000	2.098	3.147
5	6.95	113.78	0.0376	2.459	3.967	2.032	3.131
6	6.94	112.90	0.0373	2.426	3.934	2.016	3.131
7	6.92	115.53	0.0382	2.409	3.901	1.983	3.098
8	6.90	119.30	0.0395	2.377	3.852	1.934	3.081

TABLE 4.14: Natural Contaminant- Natural Wetting Test, Nishat Apartment (Location 3) March 2006

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 28.0 -29.6°C RH= 25-32%		*Natural Wet Condition* T =21.4-22.8 °C RH= 28-32%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.93	114.21	0.0347	2.459	4.065	2.049	3.262
2	6.91	116.74	0.0355	2.426	4.032	2.016	3.229
3	6.86	119.27	0.0363	2.393	4.000	1.983	3.213
4	6.84	120.54	0.0367	2.360	3.967	1.967	3.196
5	6.88	121.80	0.0371	2.327	3.934	1.934	3.180
6	6.76	123.38	0.0376	2.295	3.901	1.885	3.180
7	6.82	126.86	0.0387	2.262	3.852	1.852	3.163
8	6.78	128.74	0.0393	2.213	3.819	1.803	3.163

TABLE 4.15: Natural Contaminant- Natural Wetting Test, Nishat Apartment (Location 3) July 2006

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 31.6-33.0°C RH= 68-74%		*Natural Wet Condition* T = 27.0 -28.2°C RH= 70-78%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.93	119.97	0.0332	2.573	4.000	1.967	3.213
2	6.88	121.36	0.0336	2.524	3.967	1.934	3.180
3	6.90	124.49	0.0345	2.491	3.934	1.885	3.147
4	6.88	126.23	0.0350	2.459	3.901	1.852	3.131
5	6.79	127.96	0.0355	2.409	3.852	1.803	3.114
6	6.83	129.00	0.0358	2.360	3.819	1.754	3.098
7	6.81	132.46	0.0368	2.327	3.770	1.704	3.081
8	6.86	134.20	0.0373	2.295	3.721	1.639	3.081

TABLE 4.16: Natural Contaminant- Natural Wetting Test, Nishat Apartment (Location 3) December 2006

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 22.8 – 24.4°C RH= 28 -36%		*Natural Wet Condition* T = 17.2 -18.0°C RH= 32-36%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.85	79.42	0.0261	2.639	4.032	1.983	3.278
2	6.80	81.18	0.0267	2.606	4.000	1.934	3.245
3	6.93	85.27	0.0281	2.573	3.967	1.885	3.213
4	6.91	87.90	0.0290	2.524	3.934	1.852	3.18
5	6.79	92.27	0.0305	2.491	3.901	1.803	3.163
6	6.86	93.14	0.0308	2.459	3.852	1.754	3.147
7	6.82	94.30	0.0312	2.409	3.819	1.704	3.131
8	6.77	95.76	0.0317	2.360	3.786	1.639	3.114

TABLE 4.17: Natural Contaminant- Natural Wetting Test, Nishat Apartment (Location 3) December 2007

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 23.2– 24.6°C RH= 32– 38%		*Natural Wet Condition* T = 18.4 – 20.2°C RH= 36 – 44%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.85	89.90	0.0286	2.573	4.000	1.967	3.213
2	6.80	93.83	0.0299	2.524	3.967	1.934	3.180
3	6.93	97.45	0.0311	2.491	3.934	1.885	3.147
4	6.91	101.37	0.0324	2.459	3.901	1.852	3.131
5	6.79	105.88	0.0339	2.409	3.852	1.803	3.081
6	6.86	110.09	0.0353	2.360	3.819	1.754	3.065
7	6.82	113.38	0.0364	2.327	3.770	1.704	3.065
8	6.77	113.87	0.0364	2.295	3.721	1.639	3.049

TABLE 4.18: Natural Contaminant- Natural Wetting Test, Nishat Apartment (Location 3) March 2008

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 30.8 - 31.8°C RH= 58-64%		*Natural Wet Condition* T = 18.0 – 19.2°C RH= 76-80%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	6.89	107.14	0.0346	2.360	3.819	1.754	3.081
2	6.83	111.31	0.0360	2.327	3.770	1.704	3.032
3	6.93	113.69	0.0368	2.295	3.721	1.639	3.016
4	6.82	116.66	0.0378	2.262	3.688	1.573	3.000
5	6.79	118.44	0.0384	2.213	3.639	1.491	2.983
6	6.92	121.71	0.0395	2.147	3.606	1.426	2.95
7	6.85	127.04	0.0413	2.114	3.573	1.377	2.934
8	6.81	129.70	0.0422	2.081	3.540	1.327	2.918

TABLE 4.19: Artificial Contaminant (NaCl) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 22.4°C RH= 80%		*Natural Wet Condition* T = 19.6°C RH= 82%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.22	171.42	0.0557	1.655	3.016	1.213	2.295
2	7.23	174.68	0.0568	1.606	2.852	1.180	2.163
3	7.26	234.41	0.0771	1.524	2.721	1.098	2.131
4	7.29	253.11	0.0835	1.422	2.688	1.016	2.098
5	7.31	294.41	0.0977	1.360	2.557	0.983	2.049
6	7.34	320.76	0.1068	1.295	2.491	0.951	2.000

TABLE 4.20: Artificial Contaminant (NaCl) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 21.6°C RH= 75%		*Natural Wet Condition* T = 14.8°C RH= 90%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.21	194.47	0.0694	1.606	2.894	1.098	2.033
2	7.23	213.31	0.0764	1.540	2.786	1.016	1.983
3	7.24	224.86	0.0807	1.475	2.737	0.983	1.934
4	7.27	236.92	0.0852	1.426	2.724	0.951	1.885
5	7.30	260.95	0.0942	1.344	2.591	0.902	1.819
6	7.33	287.56	0.1042	1.295	2.571	0.836	1.770

TABLE 4.21: Artificial Contaminant (KCl) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 23.2°C RH= 80%		*Natural Wet Condition* T = 17.8 -18.4°C RH= 85 - 90%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.60	198.80	0.0665	1.655	3.639	1.065	2.262
2	7.62	207.85	0.0686	1.606	3.557	1.033	2.131
3	7.64	215.72	0.0713	1.540	3.442	1.000	2.049
4	7.66	229.39	0.0760	1.475	3.377	0.967	2.032
5	7.69	238.38	0.0791	1.393	3.327	0.918	1.950
6	7.71	250.85	0.0834	1.311	3.262	0.885	1.901

TABLE 4.22: Artificial Contaminant (KCl) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 21.2 RH= 88%		*Natural Wet Condition* T = 13.6 – 14.0°C RH= 88 -92%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.58	113.51	0.0402	1.737	3.819	1.426	2.475
2	7.62	121.93	0.0433	1.704	3.786	1.377	2.344
3	7.64	127.88	0.0455	1.656	3.77	1.344	2.278
4	7.68	197.04	0.0713	1.442	3.508	1.016	1.934
5	7.71	223.84	0.0814	1.377	3.397	0.967	1.803
6	7.75	231.77	0.0844	1.327	3.344	0.934	1.754

TABLE 4.23: Artificial Contaminant ($CaCl_2$) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 22.6°C RH= 78%		*Natural Wet Condition* T = 18.8°C RH= 88%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.44	120.27	0.0387	2.081	3.606	1.459	2.885
2	7.46	139.66	0.0452	2.000	3.54	1.393	2.786
3	7.49	154.79	0.0503	1.918	3.442	1.344	2.606
4	7.52	177.83	0.0581	1.868	3.311	1.311	2.557
5	7.55	198.41	0.0651	1.786	3.262	1.262	2.426
6	7.57	228.83	0.0755	1.704	3.131	1.213	2.362

TABLE 4.24: Artificial Contaminant ($CaCl_2$) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 22.8°C RH= 65%		*Natural Wet Condition* T = 15.2°C RH= 80%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.42	137059	0.0476	2.000	3.295	1.311	2.770
2	7.45	182040	0.0638	1.918	3.18	1.196	2.573
3	7.48	211.75	0.0745	1.836	3.098	1.098	2.475
4	7.51	218.84	0.0771	1.770	3.032	1.065	2.422
5	7.54	248.84	0.0881	1.688	2.983	1.000	2.36
6	7.56	259.19	0.0919	1.606	2.934	0.967	2.295

TABLE 4.25: Artificial Contaminant (Na_2SO_4) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 23.8°C RH=78%		*Natural Wet Condition* T = 16.4°C RH=82%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.21	121.38	0.0409	2.344	3.475	1.704	3.065
2	7.23	147.84	0.0502	2.262	3.409	1.623	2.967
3	7.26	180.03	0.0616	2.196	3.327	1.557	2.705
4	7.29	222.88	0.0769	2.115	3.246	1.492	2.573
5	7.30	288.64	0.1006	2.032	3.180	1.393	2.409
6	7.31	303.27	0.1059	1.951	3.098	1.360	2.360

TABLE 4.26: Artificial Contaminant (Na_2SO_4) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 20.6°C RH=84%		*Natural Wet Condition* T = 13.4°C RH=86%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.20	134.91	0.0481	2.229	3.754	1.606	2.901
2	7.23	154.82	0.0555	2.147	3.672	1.557	2.736
3	7.26	183.19	0.0661	2.081	3.590	1.508	2.601
4	7.29	231.51	0.0843	2.032	3.508	1.442	2.488
5	7.32	247.34	0.0903	1.983	3.426	1.328	2.401
6	7.35	288.87	0.1061	1.836	3.327	1.295	2.316

TABLE 4.27: Artificial Contaminant ($MgSO_4$) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 22.2°C RH=78%		*Natural Wet Condition* T = 18.4°C RH=84%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.44	118.04	0.0378	2.475	3.737	1.754	3.245
2	7.47	166.98	0.0542	2.393	3.688	1.689	3.031
3	7.51	205.95	0.0674	2.344	3.590	1.639	2.918
4	7.54	230.02	0.0756	2.229	3.524	1.590	2.806
5	7.59	277.57	0.0919	2.180	3.442	1.475	2.712
6	7.62	313.82	0.1044	2.081	3.361	1.409	2.606

TABLE 4.28: Artificial Contaminant ($MgSO_4$) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 21.8°C RH=80%		*Natural Wet Condition* T = 16.4°C RH=90%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.49	129.90	0.0437	2.409	3.508	1.689	3.032
2	7.52	166.62	0.0566	2.327	3.442	1.623	2.836
3	7.55	200.49	0.0686	2.262	3.361	1.573	2.772
4	7.56	236.38	0.0814	2.098	3.311	1.508	2.557
5	7.61	275.95	0.0956	2.032	3.262	1.426	2.442
6	7.64	315.29	0.1098	1.951	3.180	1.344	2.327

TABLE 4.29: Artificial Contaminant ($CaSO_4$) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 21.8°C RH=75%		*Natural Wet Condition* T = 17.6°C RH=80%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.33	111.46	0.0365	2.278	4.114	1.885	3.622
2	7.36	125.83	0.0414	2.213	4.065	1.852	3.508
3	7.38	150.02	0.0497	2.131	4.016	1.820	3.475
4	7.41	167.70	0.0558	2.049	3.934	1.754	3.409
5	7.44	190.78	0.0638	2.000	3.868	1.704	3.327
6	7.46	244.34	0.0825	1.918	3.819	1.656	3.262

TABLE 4.30: Artificial Contaminant ($CaSO_4$) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 22.2°C RH=86%		*Natural Wet Condition* T = 15.6°C RH=94%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.42	125.77	0.0428	2.361	3.672	1.656	3.278
2	7.43	188.86	0.0653	2.311	3.590	1.606	3.180
3	7.44	194.98	0.0675	2.196	3.508	1.557	3.131
4	7.44	204.74	0.0703	2.114	3.426	1.525	3.098
5	7.46	214.14	0.0744	2.032	3.344	1.475	2.983
6	7.47	220.23	0.0766	1.967	3.262	1.442	2.868

TABLE 4.31: Artificial Contaminant ($NaNO_3$) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 21.4°C RH=78%		*Natural Wet Condition* T = 16.8°C RH=82%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.24	123.46	0.0411	2.082	3.377	1.573	2.770
2	7.27	151.67	0.0509	2.000	3.295	1.508	2.688
3	7.29	197.87	0.0671	1.934	3.229	1.459	2.557
4	7.31	232.68	0.0794	1.868	3.147	1.409	2.475
5	7.34	257.16	0.0881	1.819	3.065	1.328	2.377
6	7.38	307.83	0.1062	1.737	2.967	1.278	2.196

TABLE 4.32: Artificial Contaminant ($NaNO_3$) - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 20.6°C RH=82%		*Natural Wet Condition* T = 14.2°C RH=88%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.27	170.45	0.0587	1.836	3.049	1.459	2.344
2	7.31	223.77	0.0771	1.77	3.016	1.393	2.229
3	7.34	251.08	0.0869	1.688	2.983	1.344	2.147
4	7.36	276.62	0.0961	1.606	2.934	1.295	2.081
5	7.39	297.37	0.1036	1.557	2.852	1.245	1.934
6	7.42	320.81	0.1121	1.508	2.803	1.180	1.868

TABLE 4.33: Artificial Contaminant Ca $(NO_3)_2$ - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 21.6°C RH=72%		*Natural Wet Condition* T = 18.4°C RH=78%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.34	155.09	0.0504	2.393	3.868	1.573	3.163
2	7.36	195.47	0.0641	2.311	3.737	1.508	3.065
3	7.40	235.25	0.0777	2.262	3.655	1.426	3.016
4	7.43	274.75	0.0913	2.180	3.541	1.360	2.901
5	7.45	317.21	0.1060	2.098	3.459	1.328	2.852
6	7.47	364.60	0.1225	2.016	3.344	1.295	2.786

TABLE 4.34: Artificial Contaminant Ca $(NO_3)_2$ - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 22.4°C RH=82%		*Natural Wet Condition* T = 14.2°C RH=90%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.37	172.22	0.0609	2.361	3.737	1.541	2.983
2	7.40	199.63	0.0710	2.278	3.655	1.492	2.918
3	7.43	237.92	0.0852	2.180	3.557	1.426	2.852
4	7.46	268.76	0.0967	2.098	3.475	1.360	2.786
5	7.48	298.92	0.1080	2.016	3.393	1.311	2.688
6	7.51	324.98	0.1178	1.951	3.311	1.262	2.524

TABLE 4.35: Artificial Contaminant Mg $(NO_3)_2$ - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 21.4°C RH=76%		*Natural Wet Condition* T = 17.8°C RH=80%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.34	143.89	0.0472	2.409	3.540	1.541	3.262
2	7.35	159.12	0.0524	2.327	3.442	1.492	3.114
3	7.37	197.53	0.0656	2.262	3.393	1.442	2.885
4	7.38	246.58	0.0826	2.180	3.327	1.393	2.655
5	7.40	276.96	0.0932	2.114	3.245	1.344	2.524
6	7.42	304.94	0.1030	2.016	3.229	1.311	2.377

TABLE 4.36: Artificial Contaminant Mg $(NO_3)_2$ - Natural Wetting Test

Sample	pH	σ (μS)	ESDD (mg/cm^2)	*Dry Condition* T = 19.8°C RH=84%		*Natural Wet Condition* T = 14.6°C RH=88%	
				Dry WSVUID (kV/cm)	Dry FOVUID (kV/cm)	Wet WSVUID (kV/cm)	Wet FOVUID (kV/cm)
1	7.35	111.80	0.0382	2.229	3.409	1.541	2.819
2	7.37	169.60	0.0589	2.147	3.311	1.475	2.672
3	7.39	208.52	0.073	2.065	3.262	1.409	2.524
4	7.40	247.42	0.0872	1.883	3.196	1.344	2.344
5	7.42	276.03	0.0977	1.814	3.147	1.295	2.327
6	7.45	317.779	0.1131	1.785	3.065	1.245	2.229

TABLE 4.37: Artificial Contaminant (NaCl + $CaSO_4$) - Natural Wetting Test

T =15.4°C, RH =84%

Sample	$CaSO_4$ (% by Weight)	NaCl (% by Weight)	pH	σ (μS)	ESDD (mg/cm^2)	Wet FOVUID (kV/cm)
1	10	90	7.35	274.49	0.0963	2.131
2	30	70	7.31	231.56	0.0807	2.196
3	50	50	7.27	189.14	0.0654	2.459
4	60	40	7.25	163.75	0.0563	2.672
5	70	30	7.22	134.24	0.0458	2.786
6	80	20	7.19	91.91	0.0309	2.885

TABLE 4.38: Artificial Contaminant (KCl + $CaSO_4$) - Natural Wetting Test

T =14.8°C, RH =88%

Sample	$CaSO_4$ (% by Weight)	KCl (% by Weight)	pH	σ (μS)	ESDD (mg/cm^2)	Wet FOVUID (kV/cm)
1	10	90	7.54	254.02	0.0904	1.852
2	30	70	7.49	211.96	0.0749	2.098
3	50	50	7.46	179.17	0.0629	2.285
4	60	40	7.42	155.25	0.0542	2.459
5	70	30	7.39	132.86	0.0461	2.655
6	80	20	7.37	71.71	0.0241	3.015

TABLE 4.39: Artificial Contaminant (NaCl + CaO) - Natural Wetting Test

T =14.4°C, RH =86%

Sample	CaO (% by Weight)	NaCl (% by Weight)	pH	σ (μS)	ESDD (mg/cm^2)	Wet FOVUID (kV/cm)
1	10	90	7.47	217.07	0.0778	2.622
2	30	70	7.44	187.73	0.0669	2.754
3	50	50	7.42	162.81	0.0577	2.819
4	60	40	7.40	141.03	0.0497	2.983
5	70	30	7.36	125.69	0.0441	3.196
6	80	20	7.31	107.26	0.0374	3.311

TABLE 4.40: Artificial Contaminant (KCl + CaO) - Natural Wetting Test

T =14.6°C, RH =82%

Sample	CaO (% by Weight)	KCl (% by Weight)	pH	σ (μS)	ESDD (mg/cm^2)	Wet FOVUID (kV/cm)
1	10	90	7.47	216.40	0.0762	2.442
2	30	70	7.44	209.01	0.0735	2.524
3	50	50	7.42	183.50	0.0642	2.606
4	60	40	7.40	161.16	0.0561	2.688
5	70	30	7.36	127.84	0.0441	2.836
6	80	20	7.31	103.46	0.0354	3.049

TABLE 4.41: Artificial Contaminant ($CaSO_4$ + CaO) - Natural Wetting Test

T =16.0°C, RH =80%

Sample	CaO (% by Weight)	$CaSO_4$ (% by Weight)	pH	σ (μS)	ESDD (mg/cm^2)	Wet FOVUID (kV/cm)
1	10	90	7.66	193.74	0.0662	3.114
2	30	70	7.59	180.20	0.0614	3.295
3	50	50	7.55	161.24	0.0547	3.360
4	60	40	7.51	139.04	0.0469	3.442
5	70	30	7.48	122.17	0.0410	3.491
6	80	20	7.45	102.03	0.0340	3.540

TABLE 4.42: Artificial Contaminant (Mg $(NO_3)_2$ + CaO) - Natural Wetting Test

T =15.6°C, RH =78%

Sample	CaO (% by Weight)	$Mg(NO_3)_2$ (% by Weight)	pH	σ (μS)	ESDD (mg/cm^2)	Wet FOVUID (kV/cm)
1	10	90	7.54	176.77	0.0607	2.786
2	30	70	7.51	158.51	0.0542	2.852
3	50	50	7.49	135.36	0.0460	2.901
4	60	40	7.44	125.44	0.0425	2.918
5	70	30	7.42	106.34	0.0358	2.983
6	80	20	7.39	91.15	0.0305	3.049

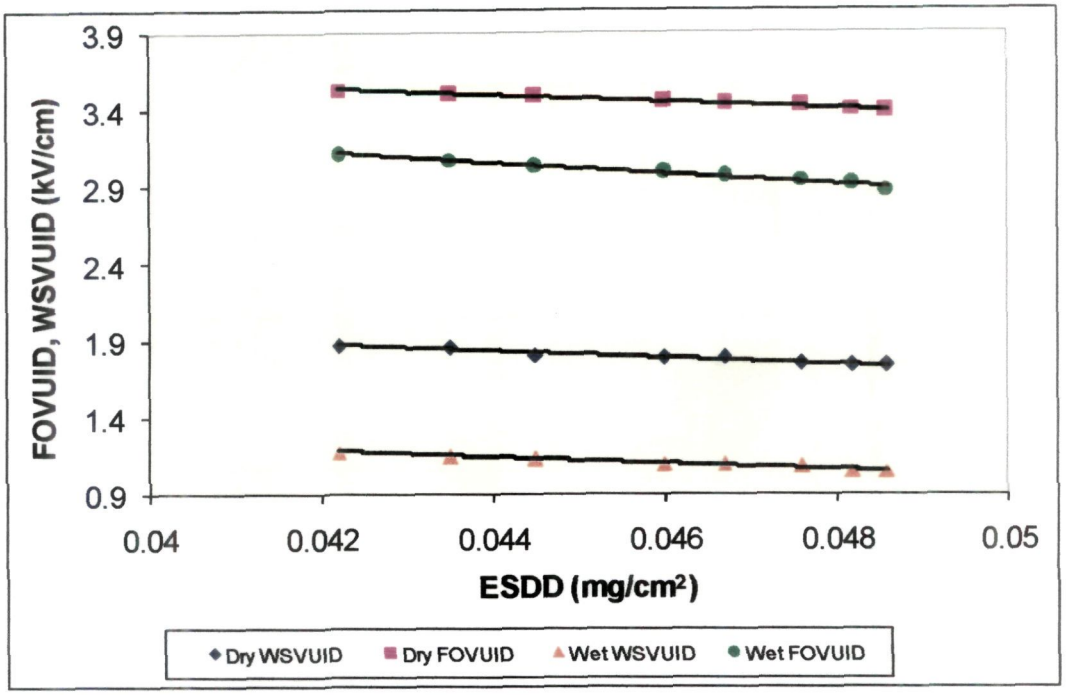


Fig. 4.1: FOVUID, WSVUID vs ESDD Curve for NH-91 Dec. 2005.

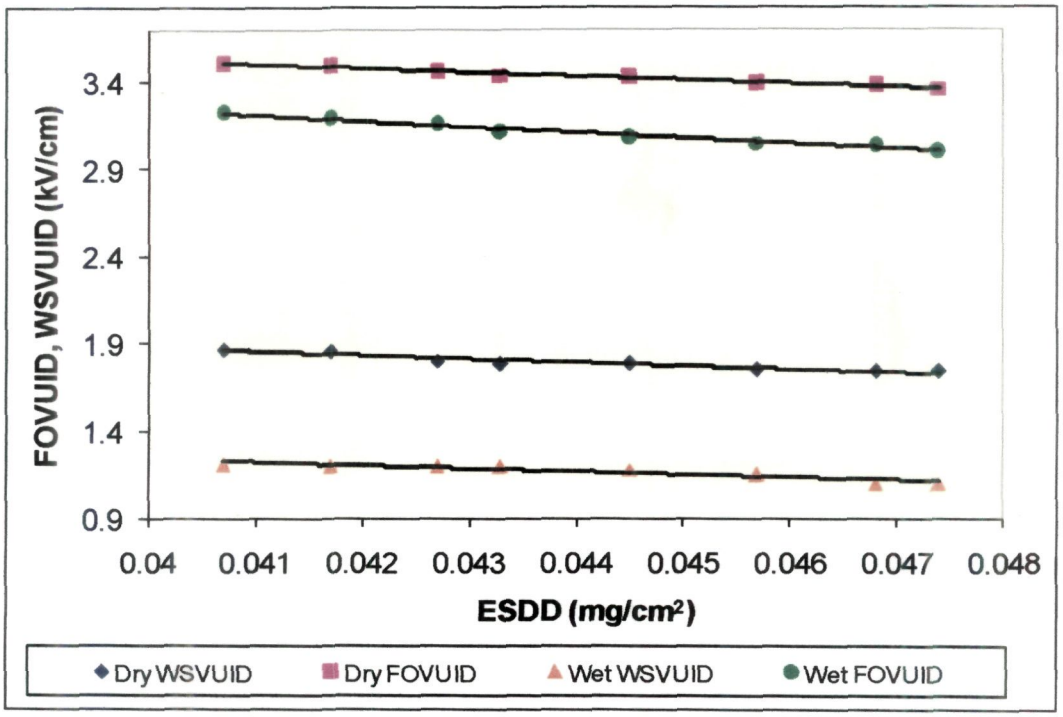


Fig. 4.2: FOVUID, WSVUID vs ESDD Curve for NH-91 March 2006.

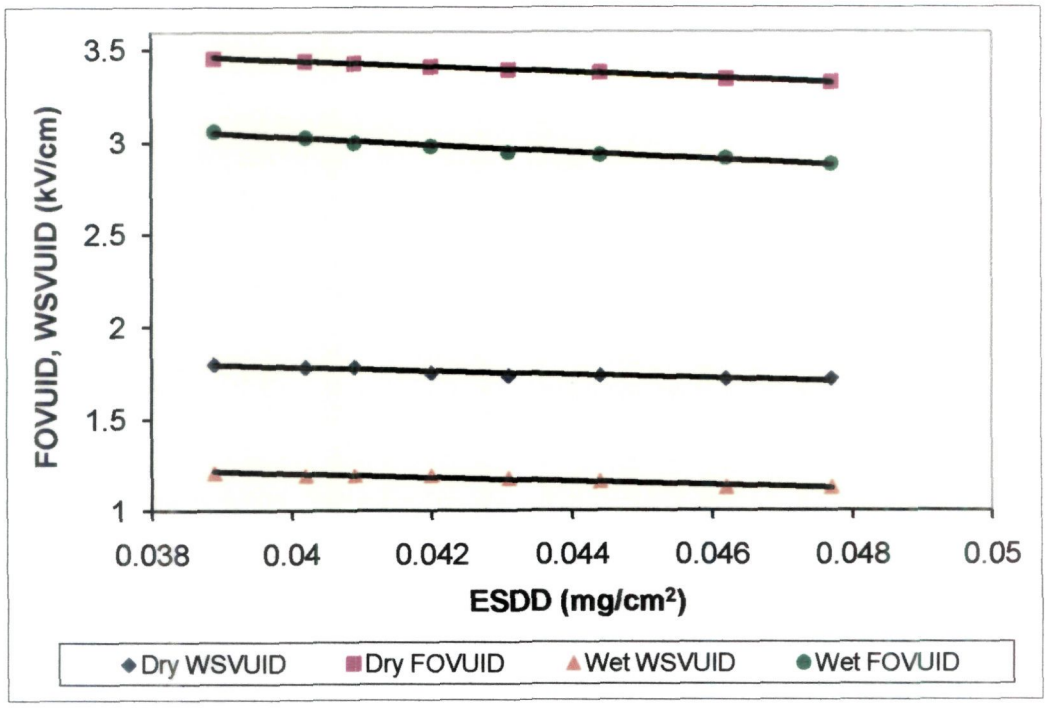


Fig. 4.3: FOVUID, WSVUID vs ESDD Curve for NH-91 July 2006.

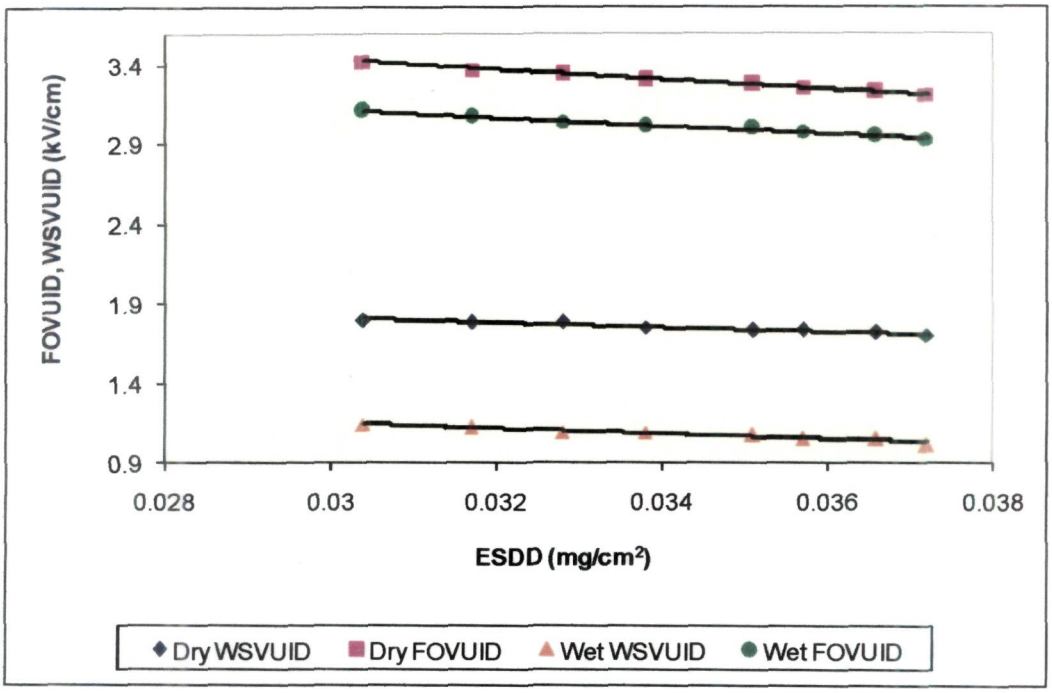


Fig. 4.4: FOVUID, WSVUID vs ESDD Curve for NH-91 Dec. 2006.

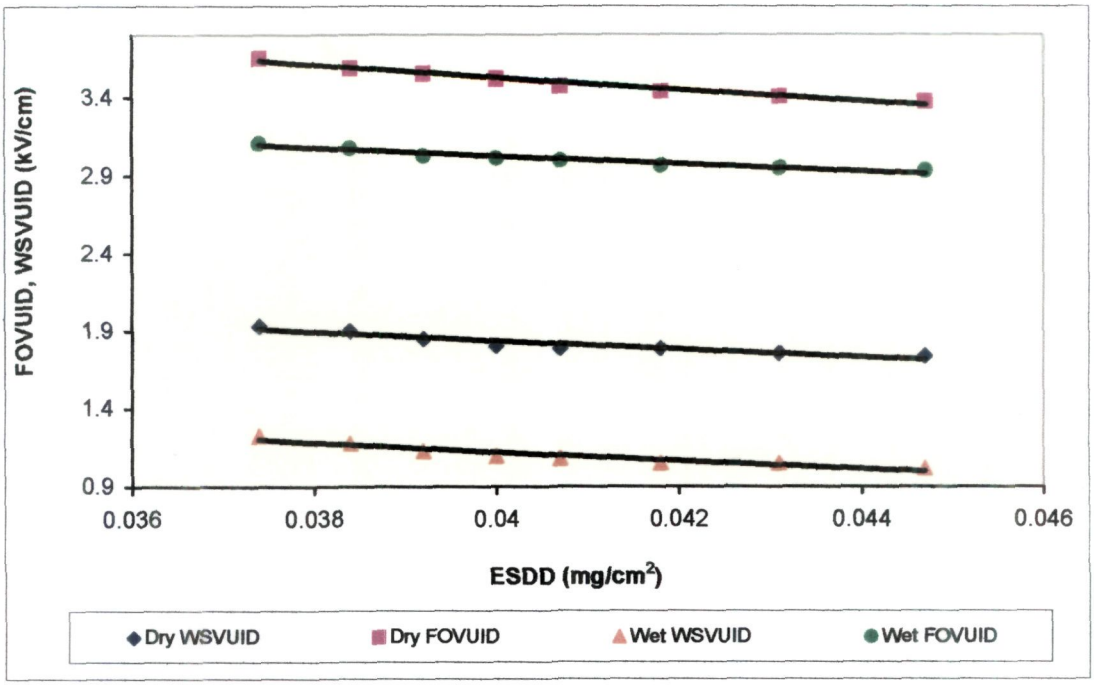


Fig. 4.5: FOVUID, WSVUID vs ESDD Curve for NH-91 Dec. 2007.

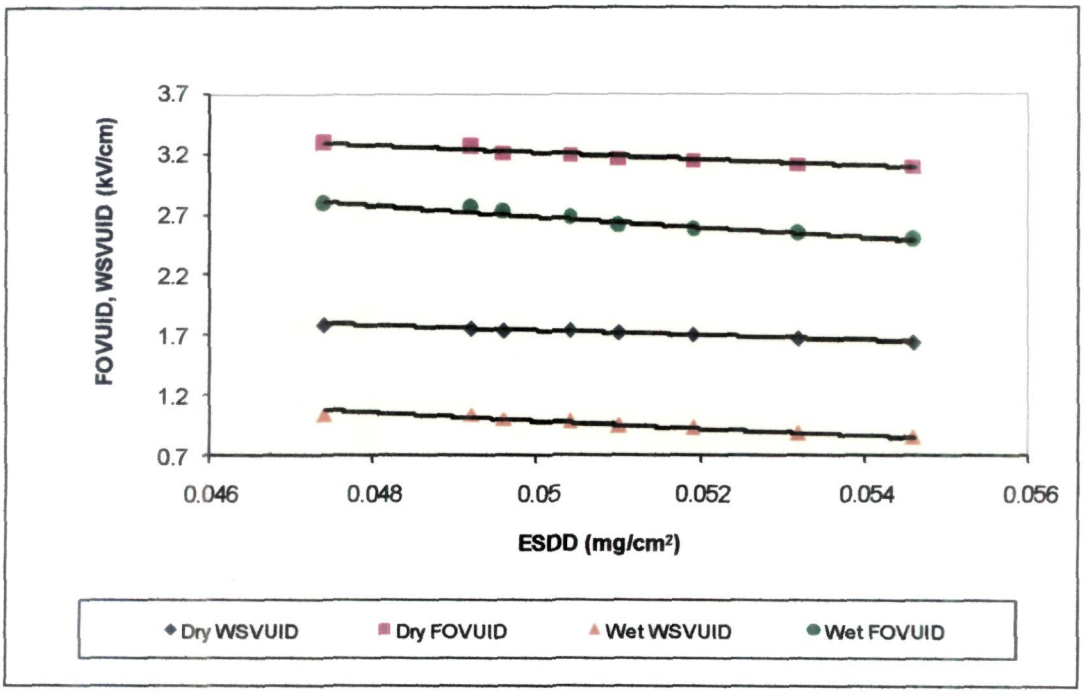


Fig. 4.6: FOVUID, WSVUID vs ESDD Curve for NH-91 March 2008.

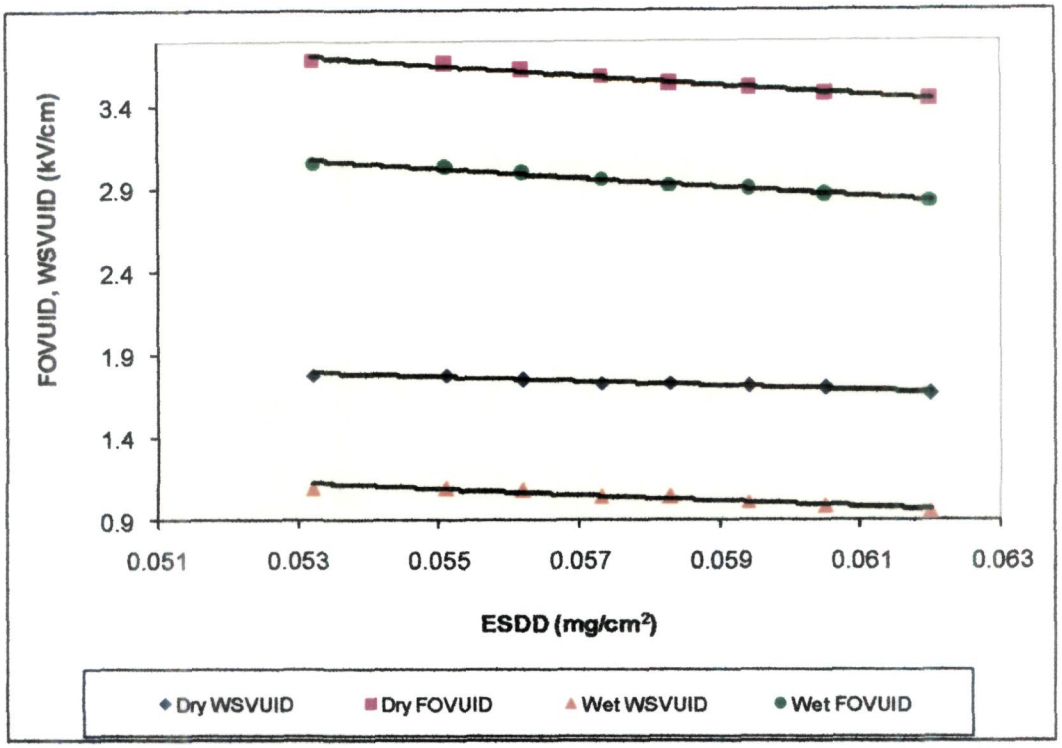


Fig. 4.7: FOVUID, WSVUID vs ESDD Curve for Thermal Plant Dec. 2005.

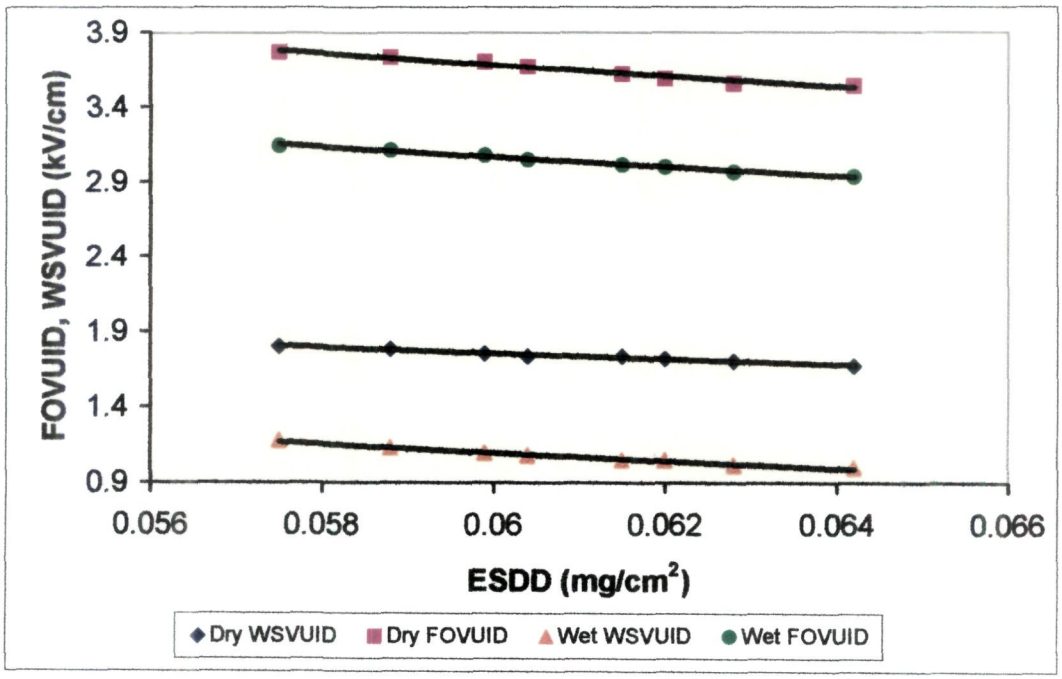


Fig. 4.8: FOVUID, WSVUID vs ESDD Curve for Thermal Plant March 2006

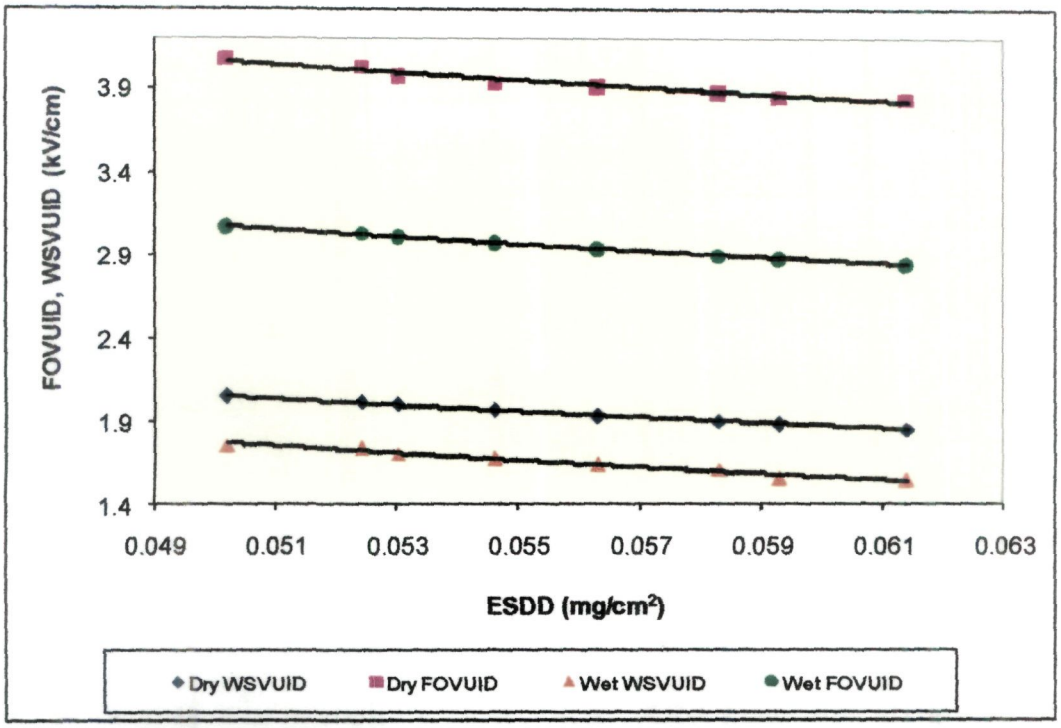


Fig. 4.9: FOVUID, WSVUID vs ESDD Curve for Thermal Plant July 2006

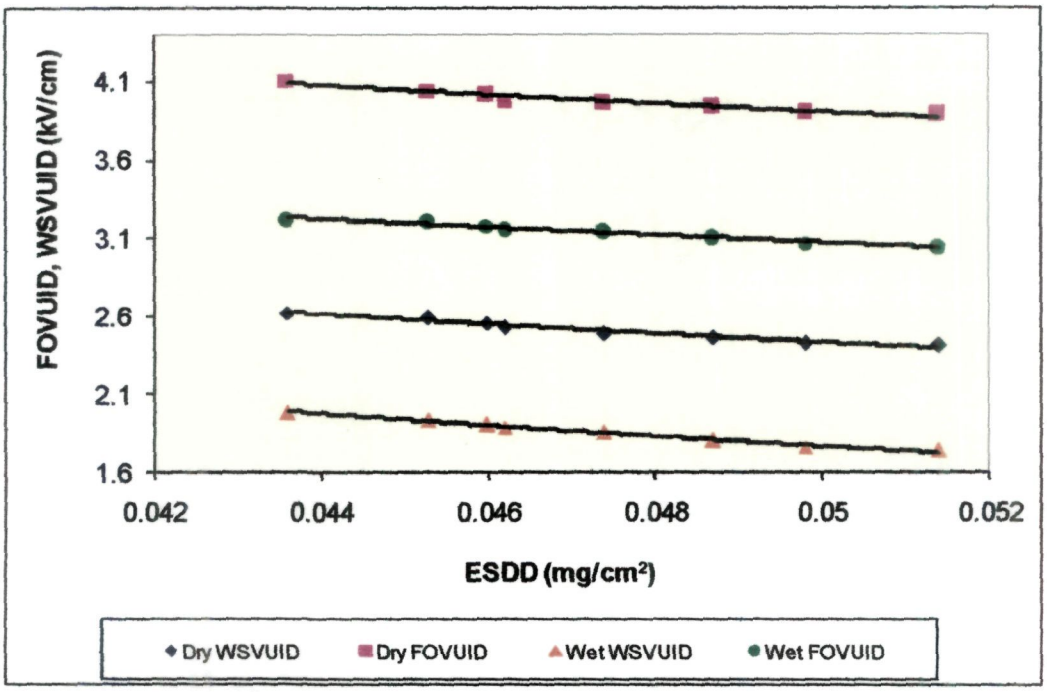


Fig. 4.10: FOVUID, WSVUID vs ESDD Curve for Thermal Plant Dec 2006

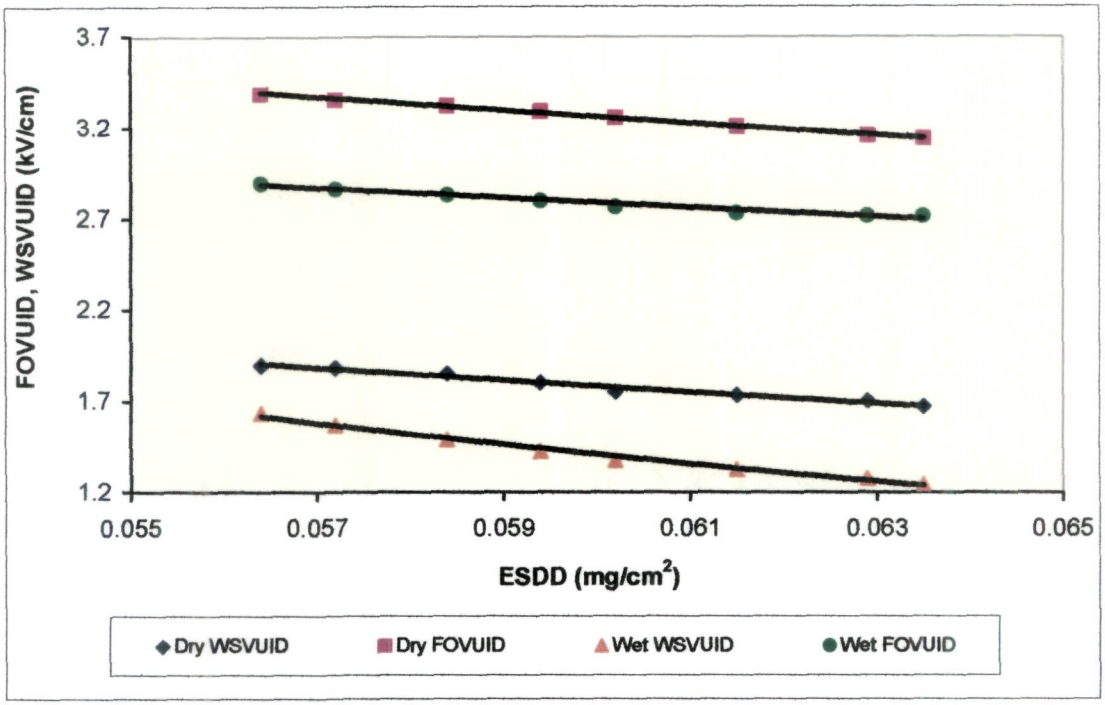


Fig. 4.11: FOVUID, WSVUID vs ESDD Curve for Thermal Plant Dec 2007

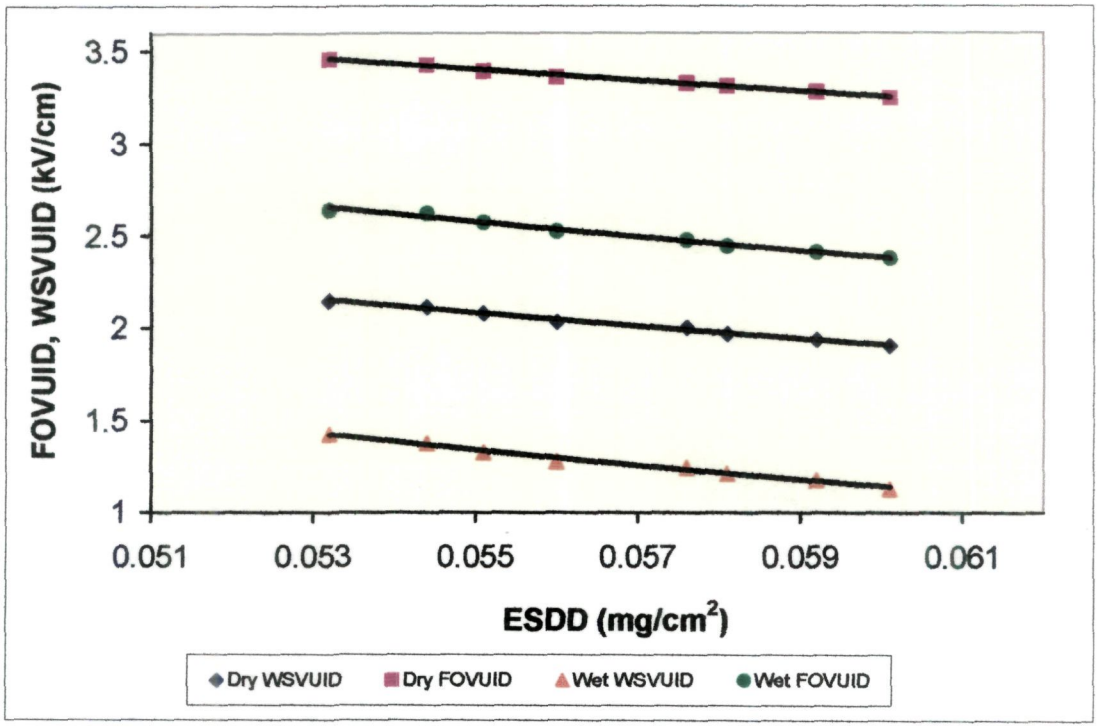


Fig. 4.12: FOVUID, WSVUID vs ESDD Curve for Thermal Plant March 2008

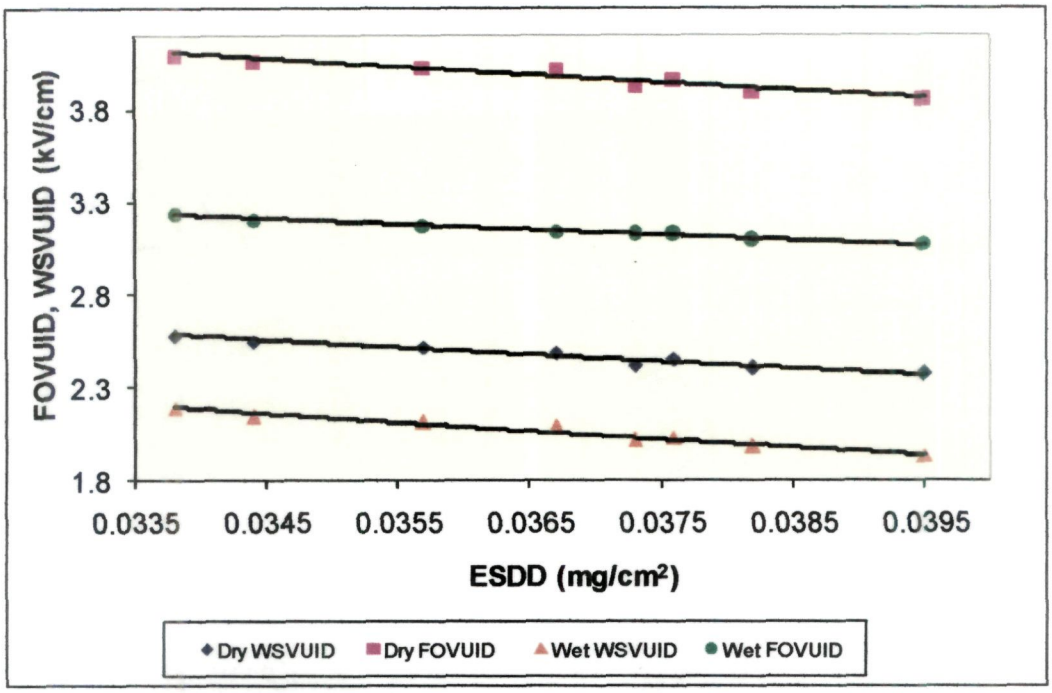


Fig. 4.13: FOVUID, WSVUID vs ESDD Curve for Nishat Apartment Dec 2005

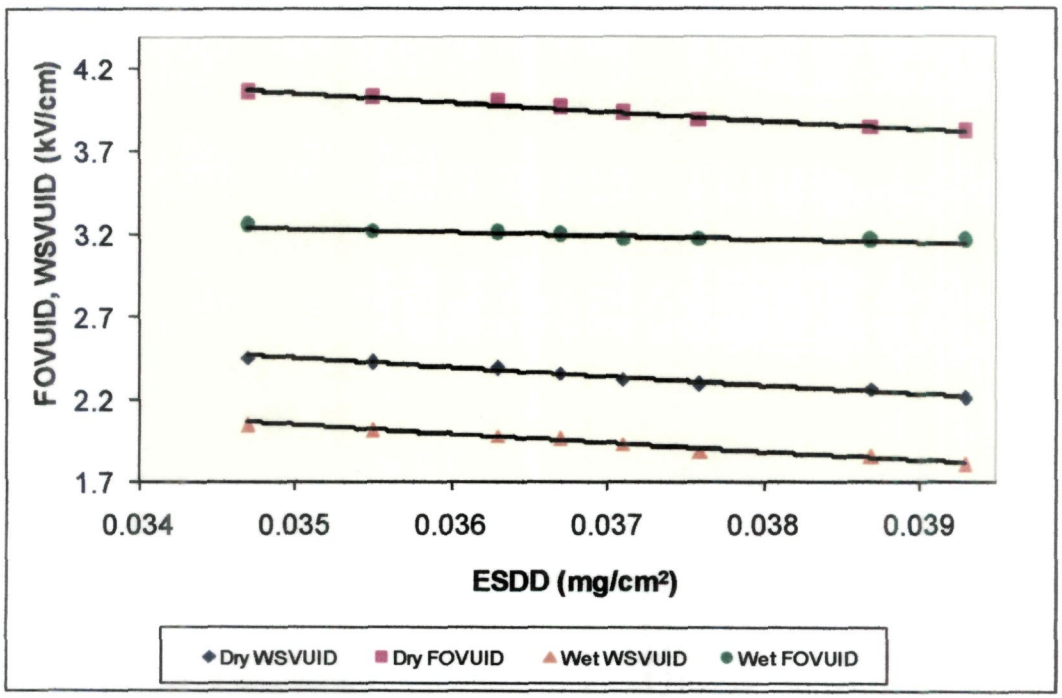


Fig. 4.14: FOVUID, WSVUID vs ESDD Curve for Nishat Apartment March 2006

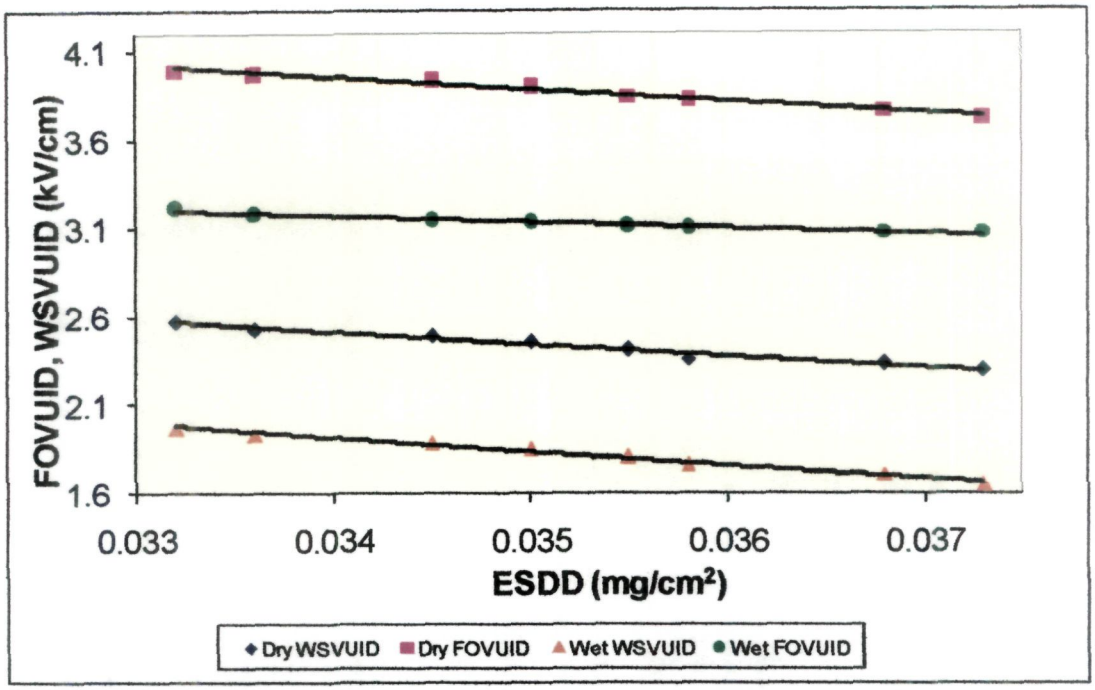


Fig. 4.15: FOVUID, WSVUID vs ESDD Curve for Nishat Apartment July 2006

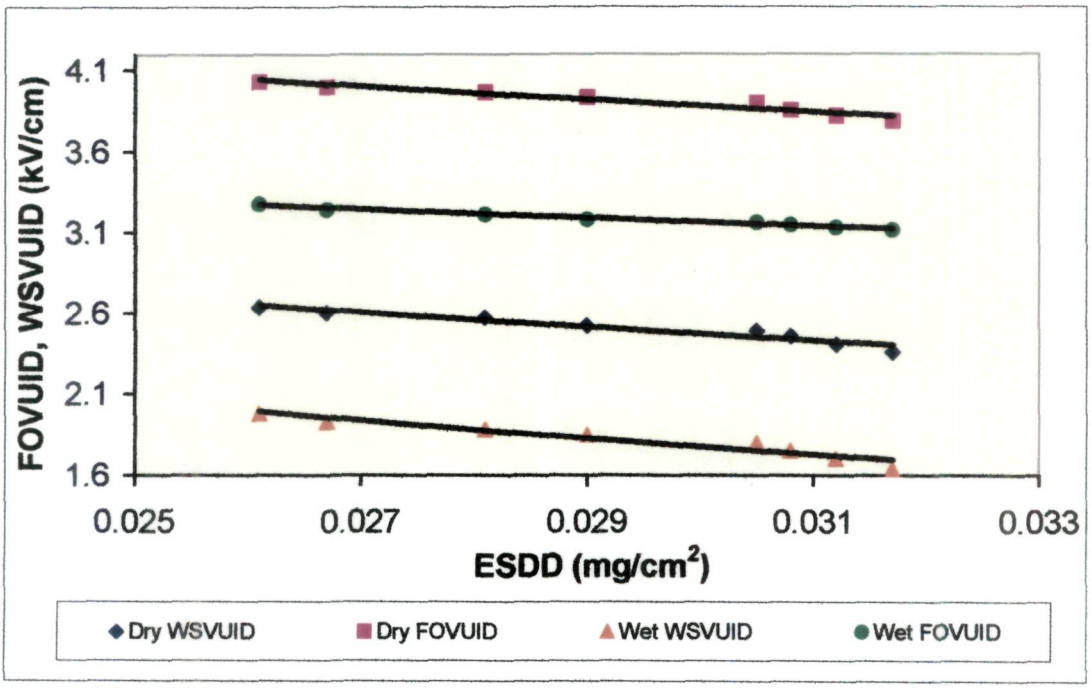


Fig. 4.16: FOVUID, WSVUID vs ESDD Curve for Nishat Apartment Dec 2006

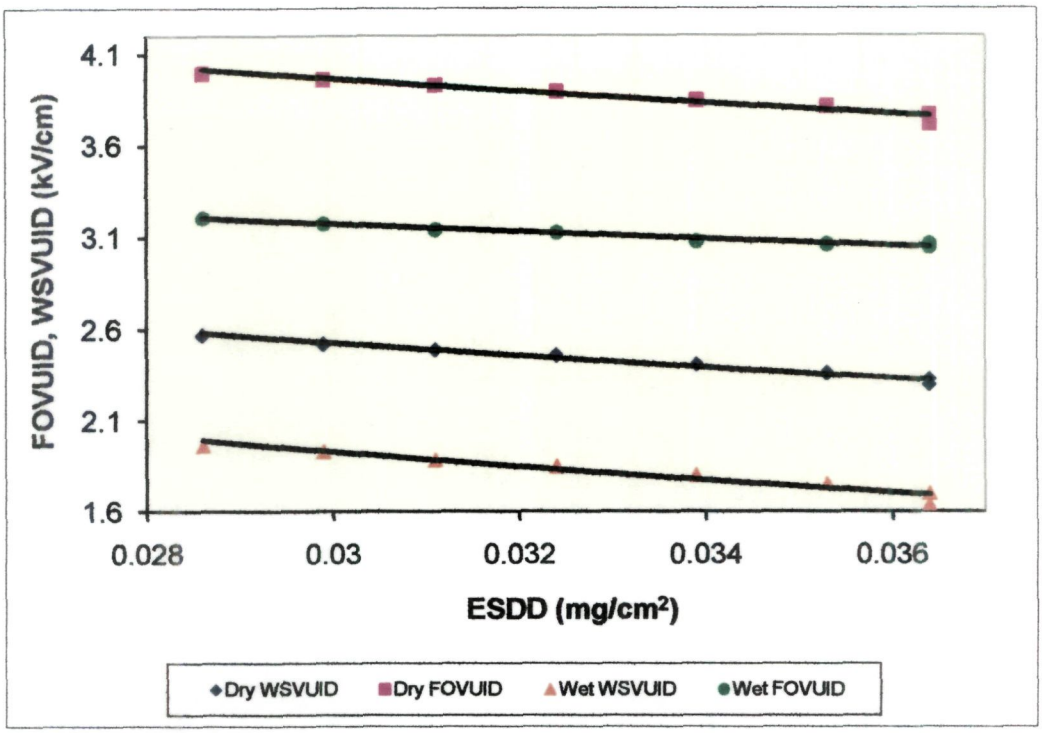


Fig. 4.17: FOVUID, WSVUID vs ESDD Curve for Nishat Apartment Dec 2007

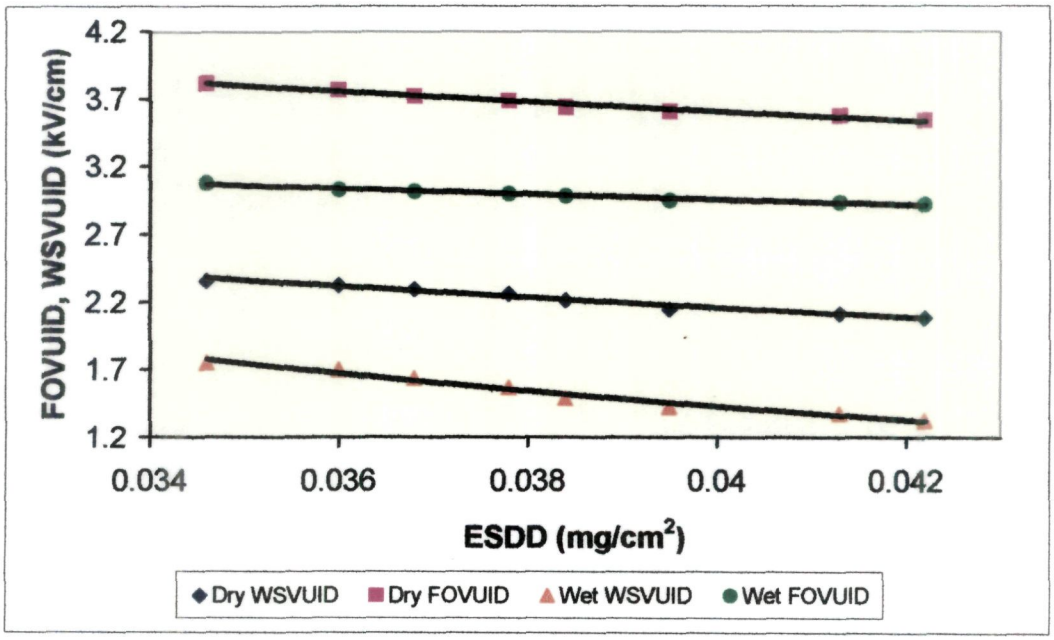


Fig. 4.18: FOVUID, WSVUID vs ESDD Curve for Nishat Apartment March 2008

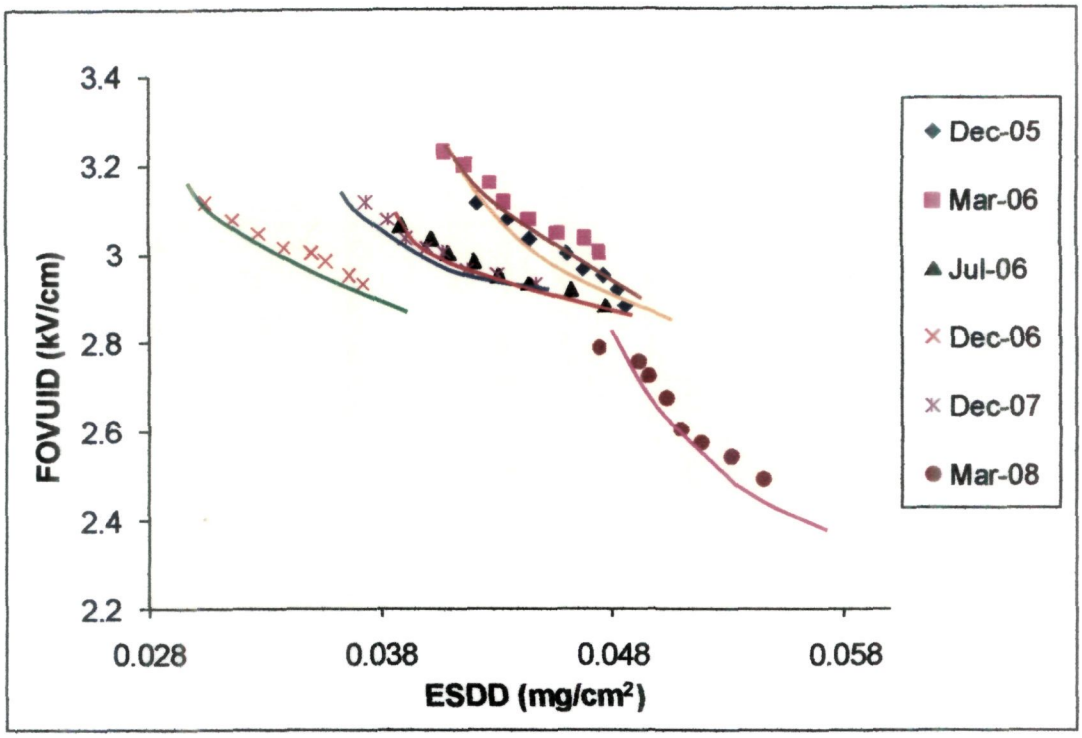


Fig. 4.19: Comparative graph FOVUID vs ESDD for NH-91

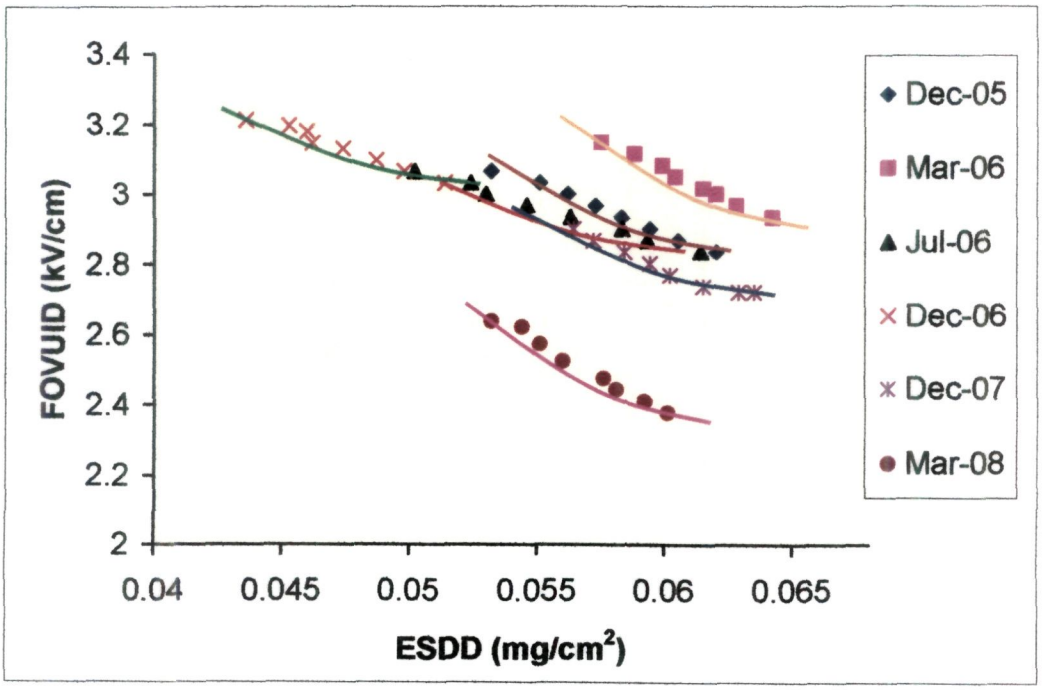


Fig. 4.20: Comparative graph FOVUID vs ESDD for Thermal Plant

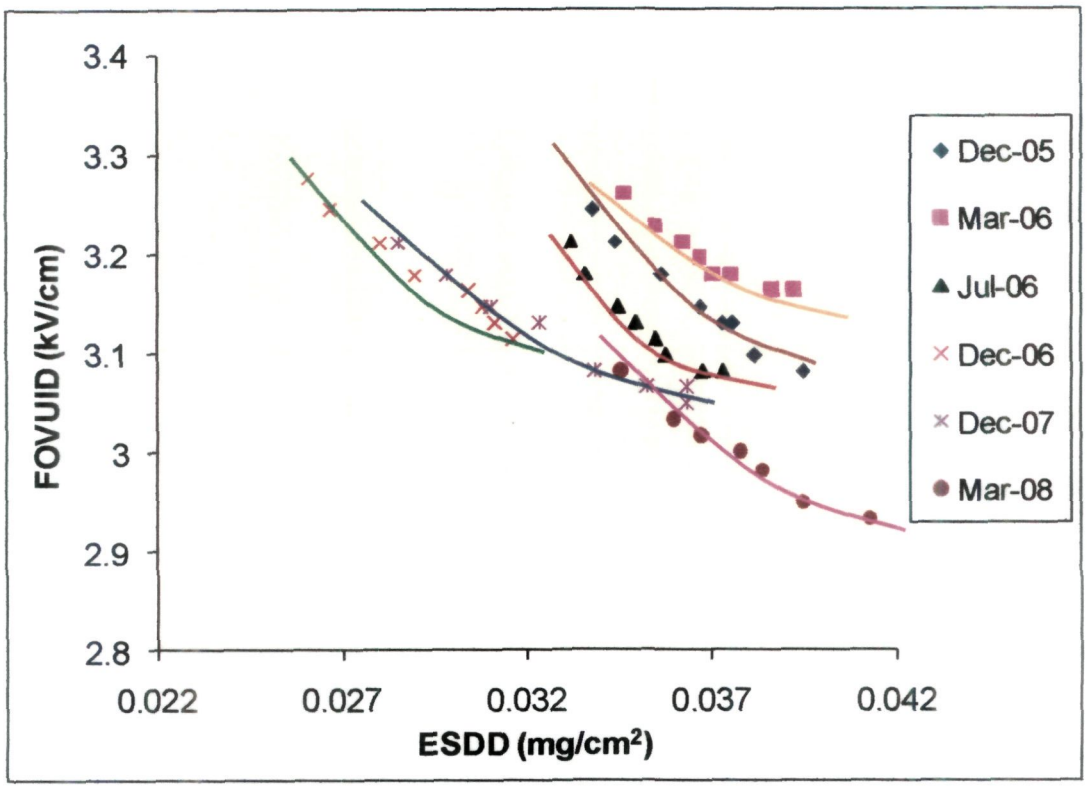


Fig. 4.21: Comparative graph FOVUID vs ESDD for Nishat Apartment

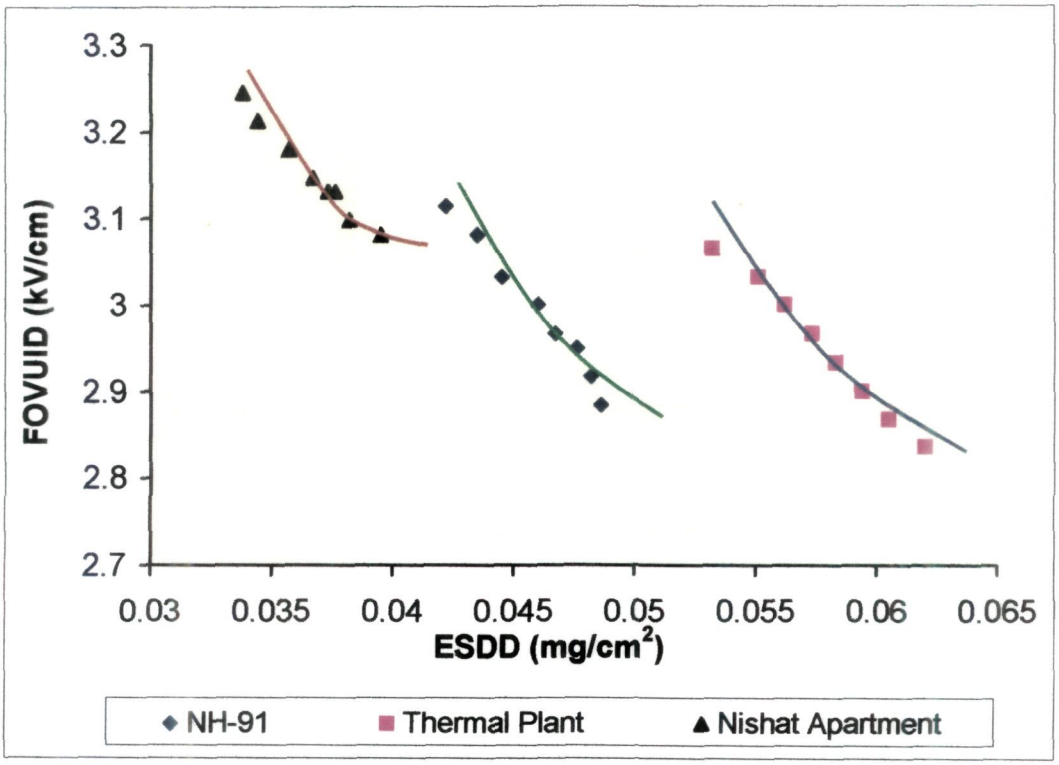


Fig. 4.22: Comparative graph FOVUID vs ESDD for the three sites Dec. 2005.

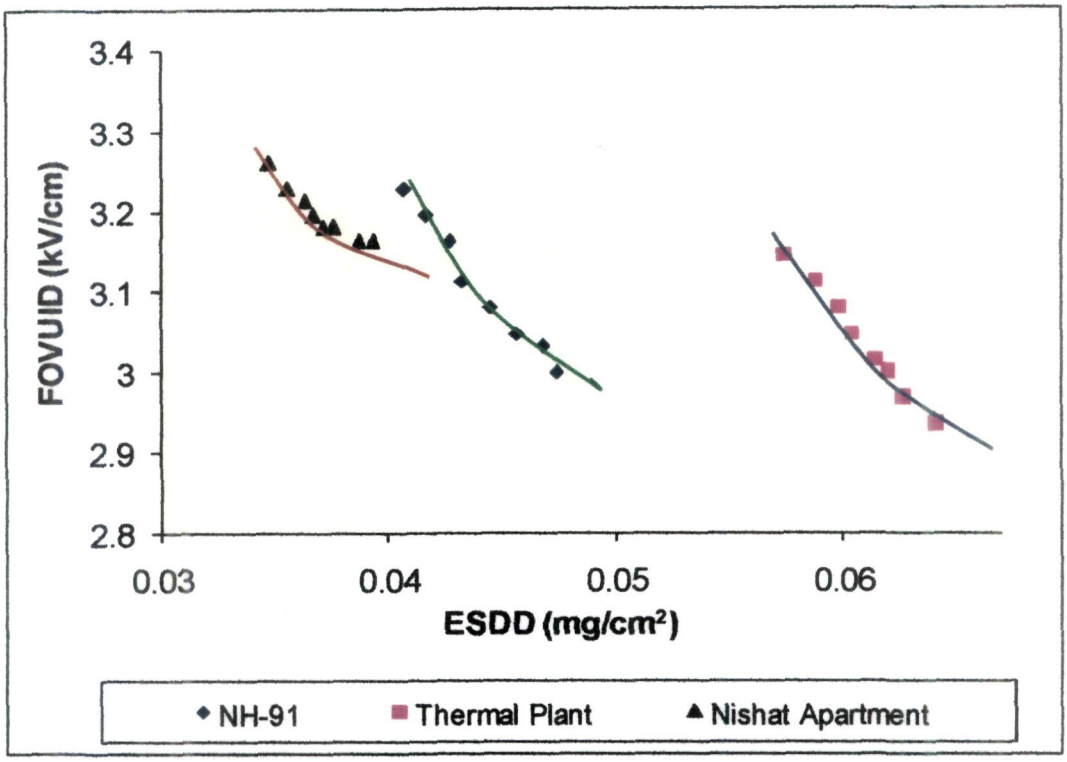


Fig. 4.23: Comparative graph FOVUID vs ESDD for the three sites March 2006.

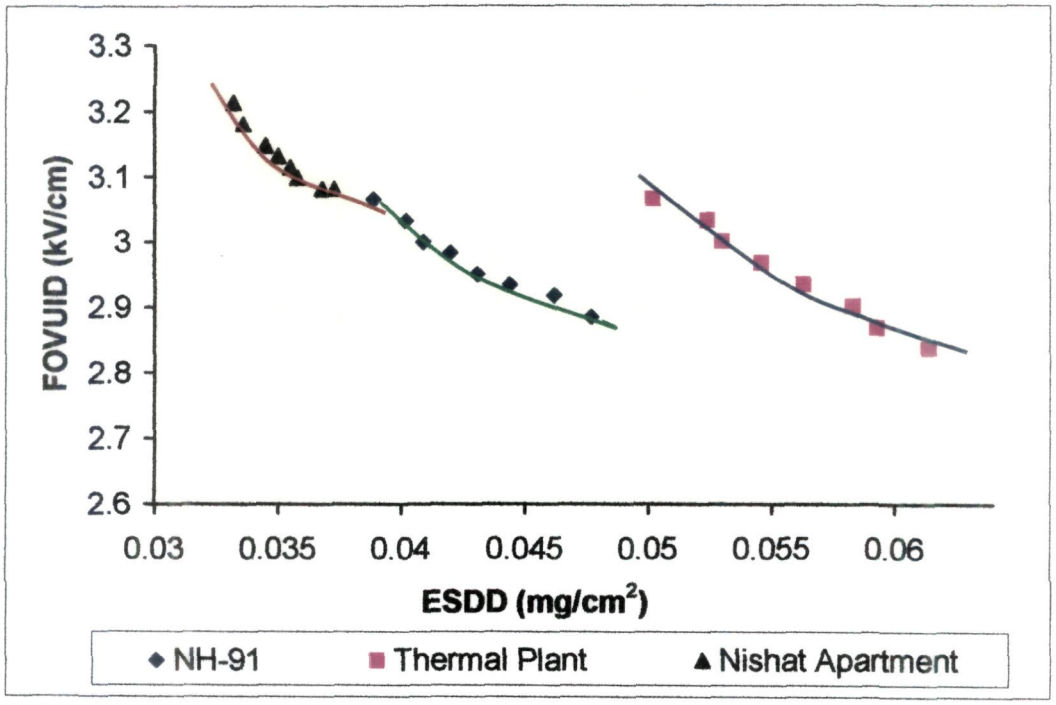


Fig. 4.24: Comparative graph FOVUID vs ESDD for the three sites July 2006.

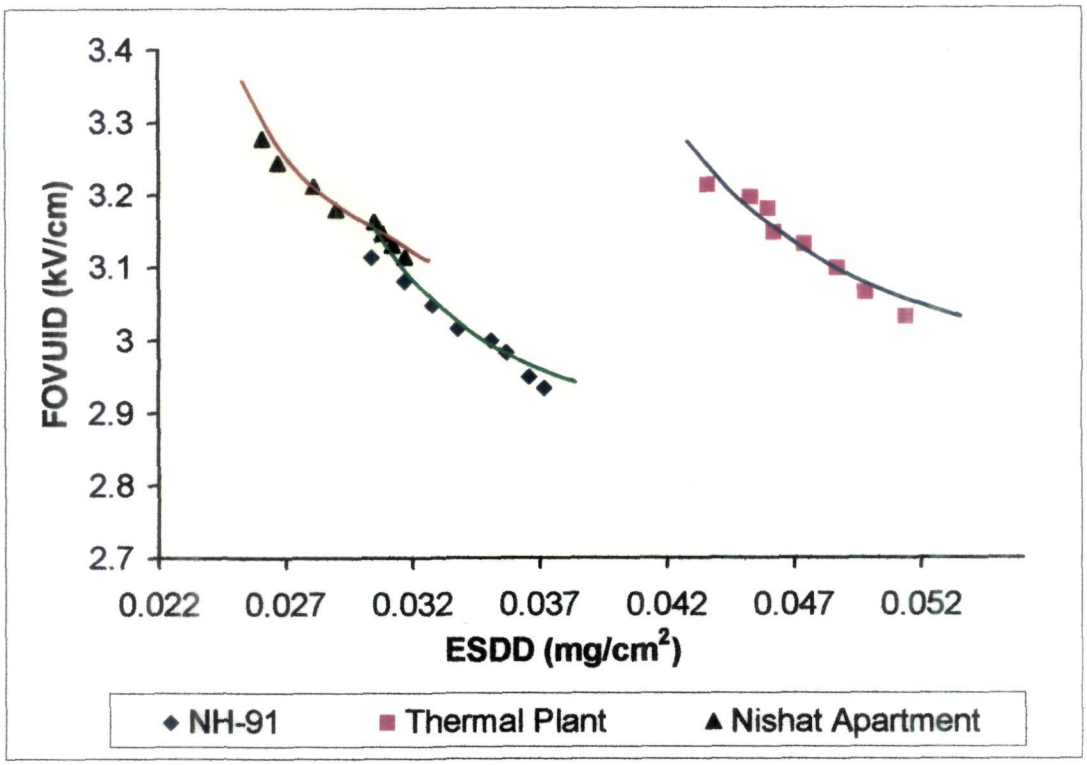


Fig. 4.25: Comparative graph FOVUID vs ESDD for the three sites Dec. 2006.

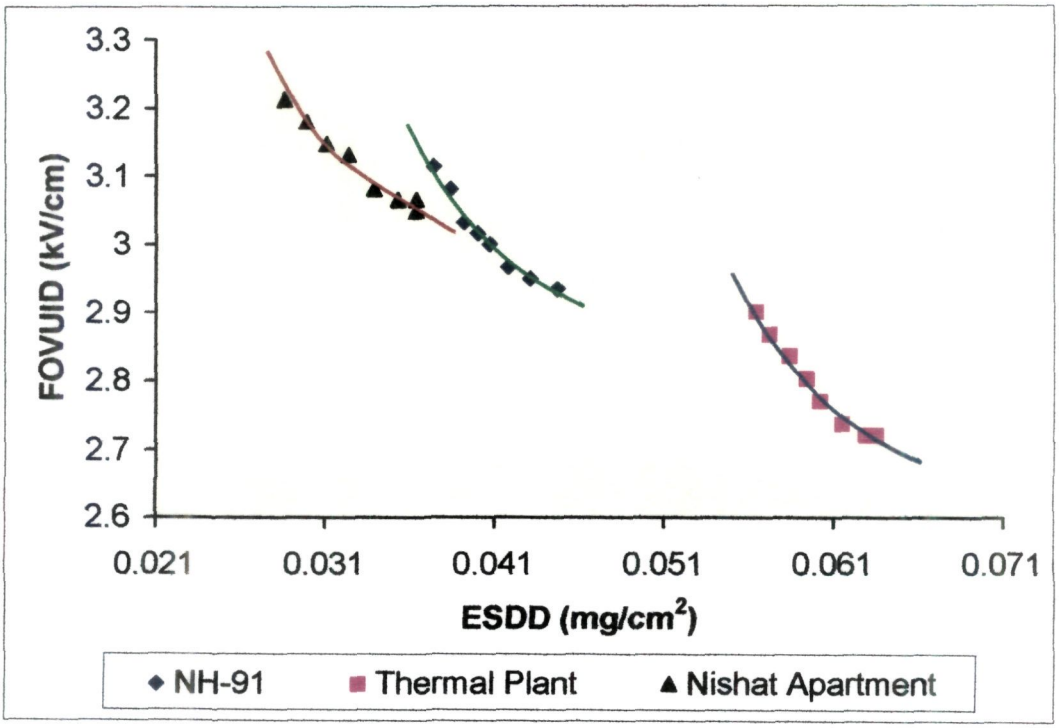


Fig. 4.26: Comparative graph FOVUID vs ESDD for the three sites Dec. 2007.

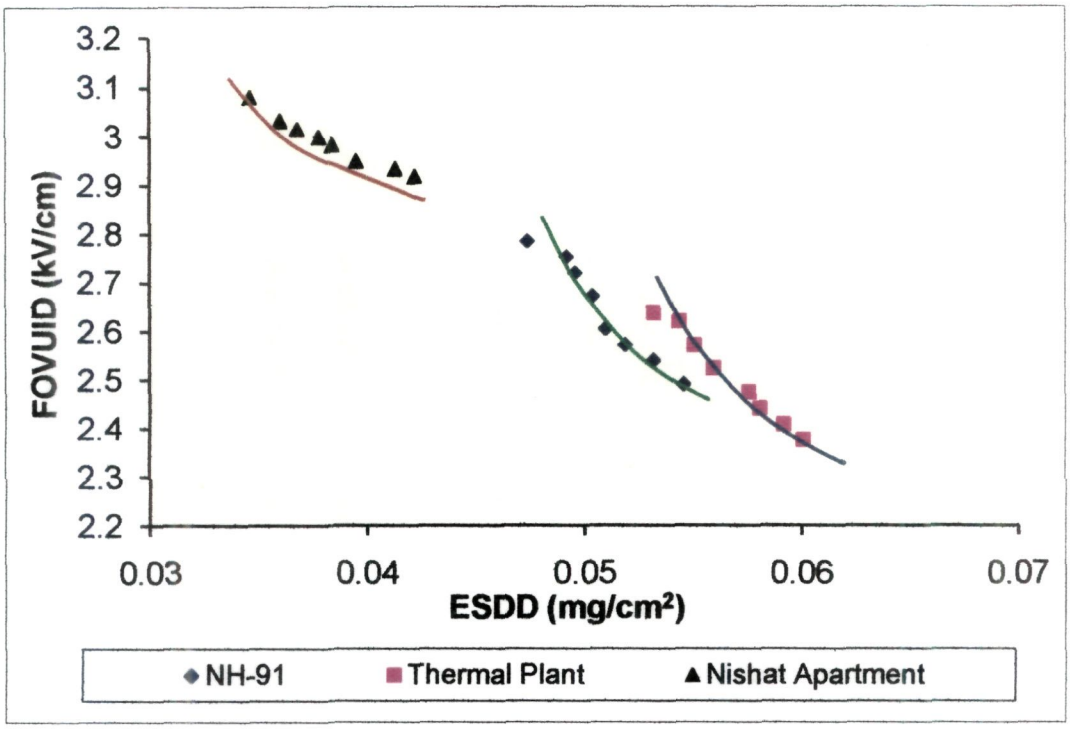


Fig. 4.27: Comparative graph FOVUID vs ESDD for the three sites March 2008.

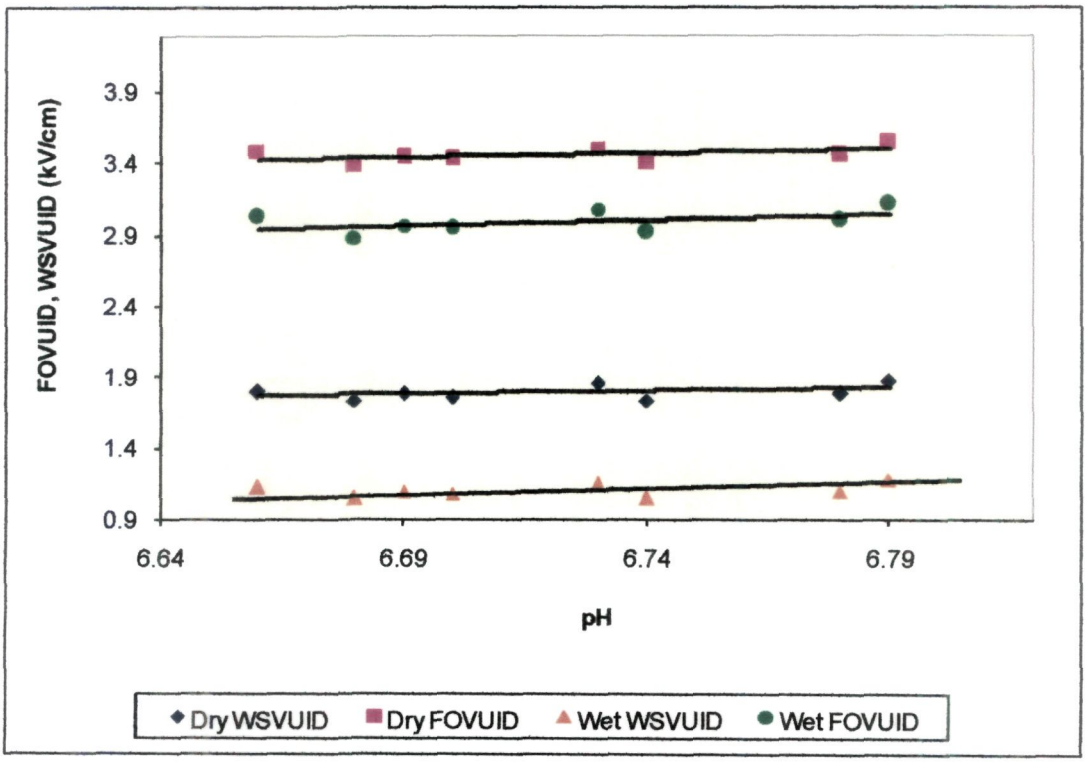


Fig.4.28: FOVUID, WSVUID vs pH Curve for NH-91 Dec. 2005.

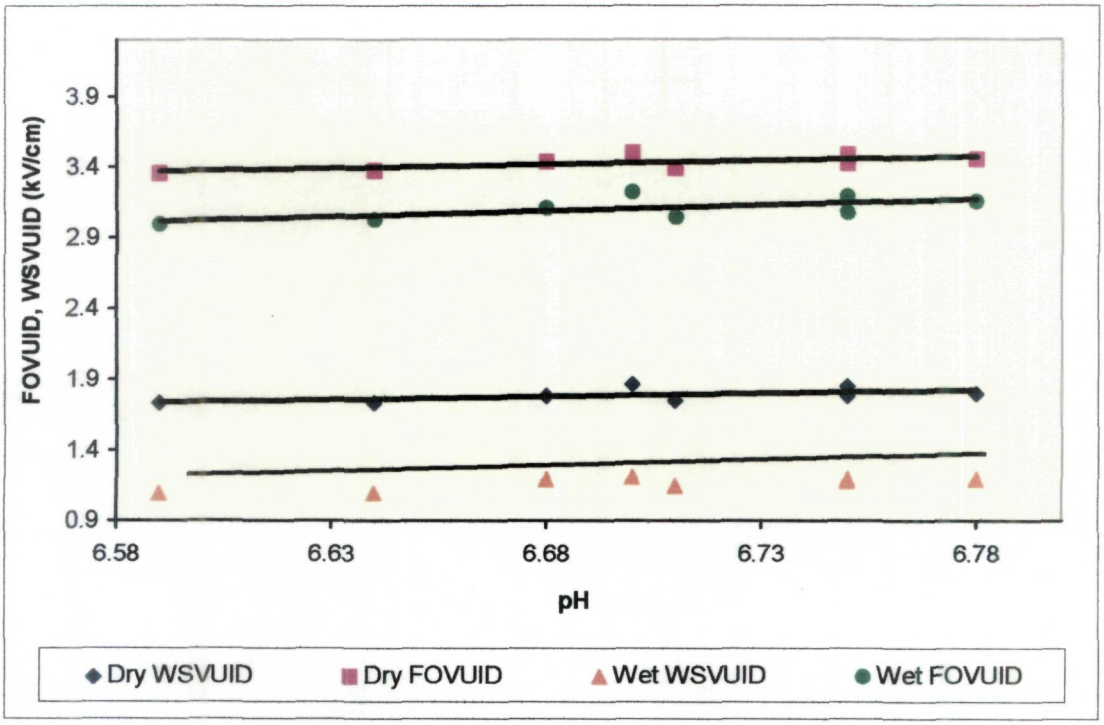


Fig.4.29 : FOVUID, WSVUID vs pH Curve for NH-91 March 2006.

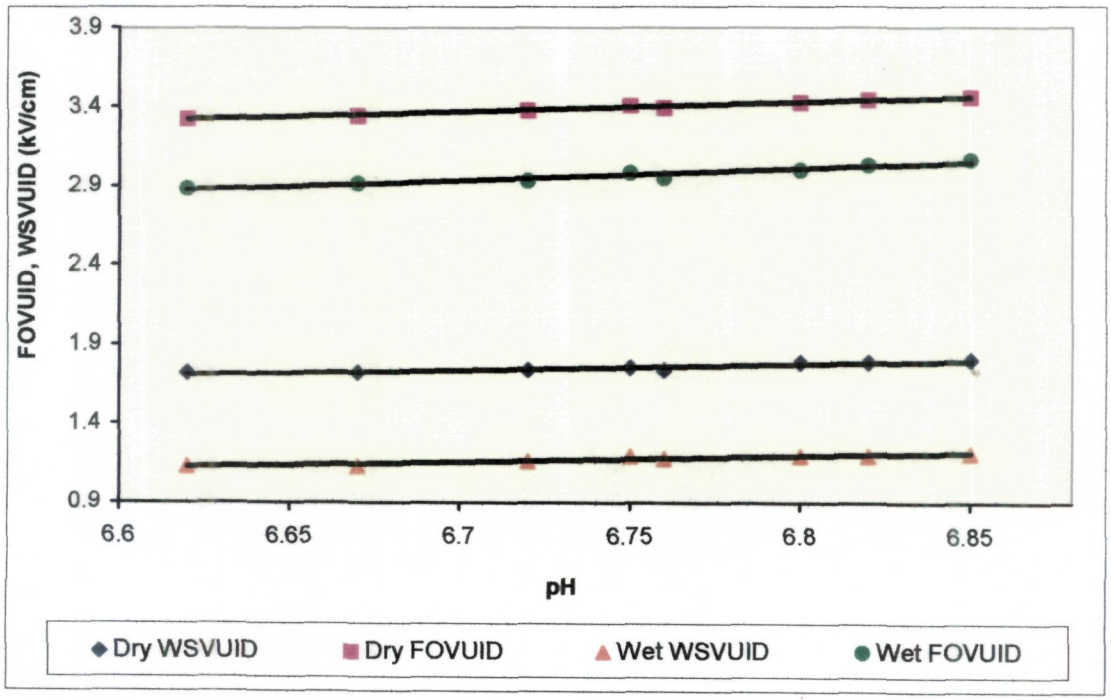


Fig.4.30: FOVUID, WSVUID vs pH Curve for NH-91 July 2006.

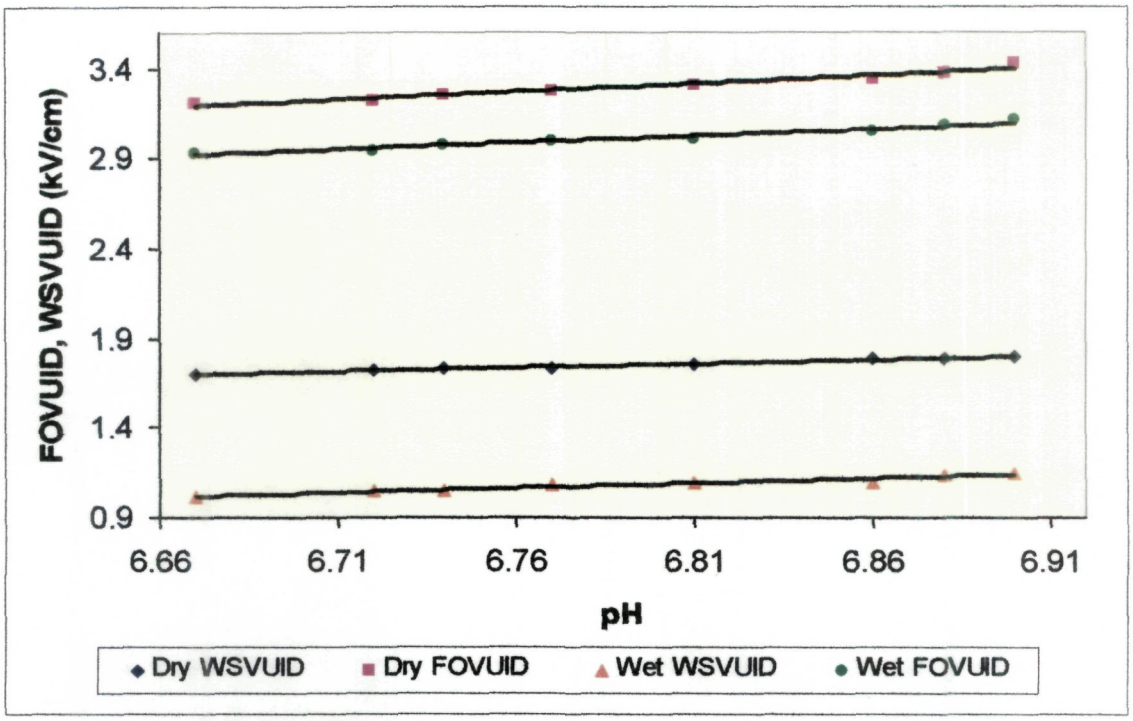


Fig. 4.31: FOVUID, WSVUID vs pH Curve for NH-91 Dec. 2006.

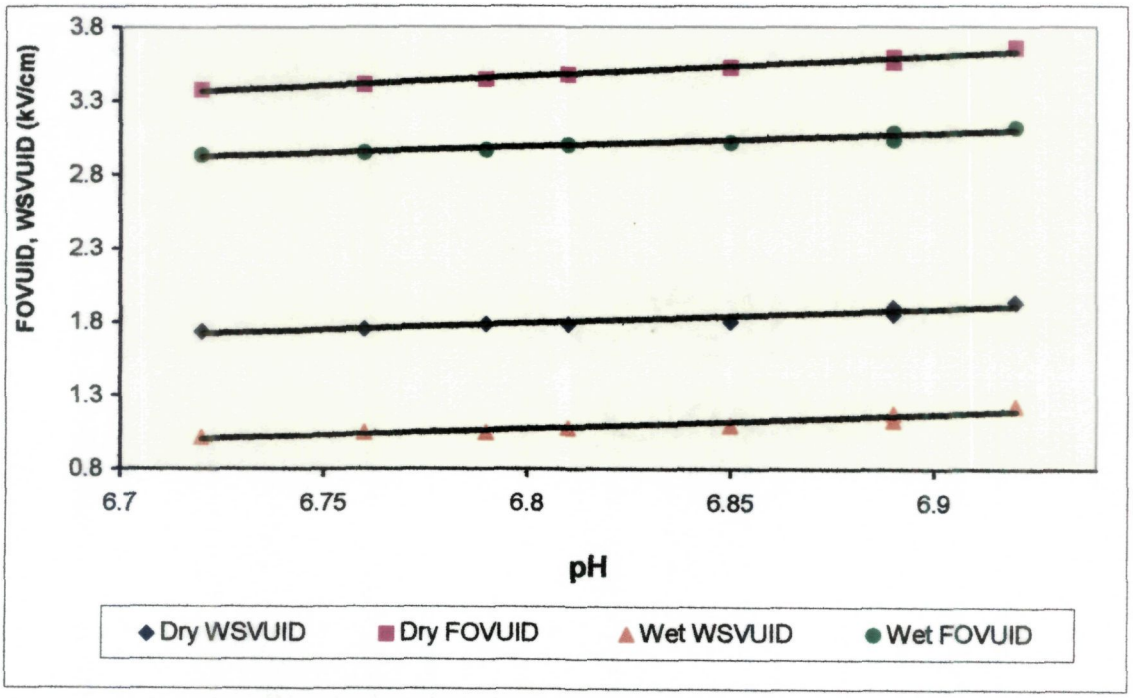


Fig.4.32: FOVUID, WSVUID vs pH Curve for NH-91 Dec. 2007.

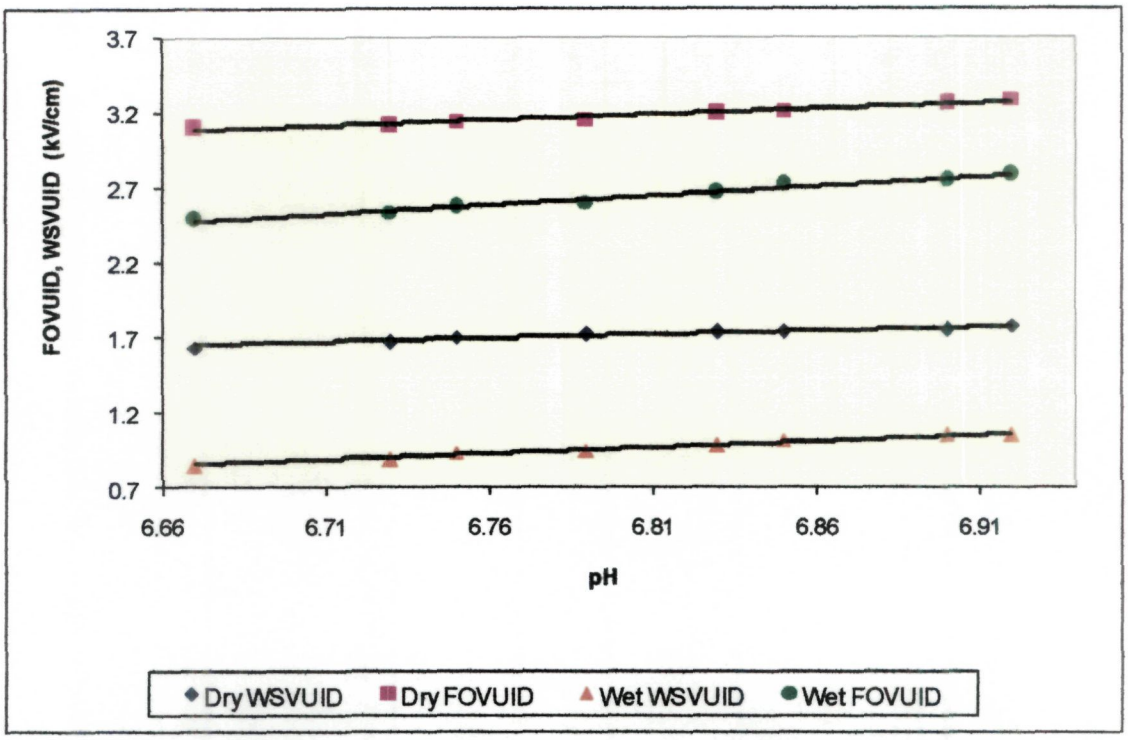


Fig. 4.33: FOVUID, WSVUID vs pH Curve for NH-91 March 2008.

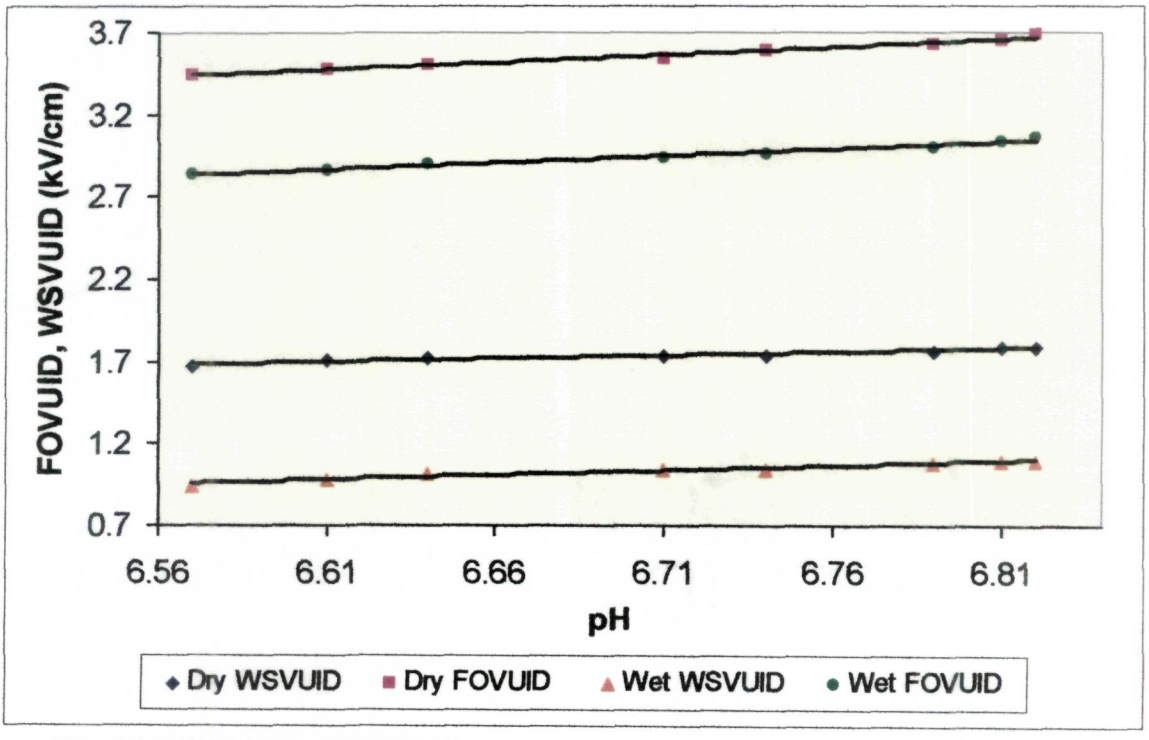


Fig.4.34: FOVUID, WSVUID vs pH Curve for Thermal Plant Dec. 2005.

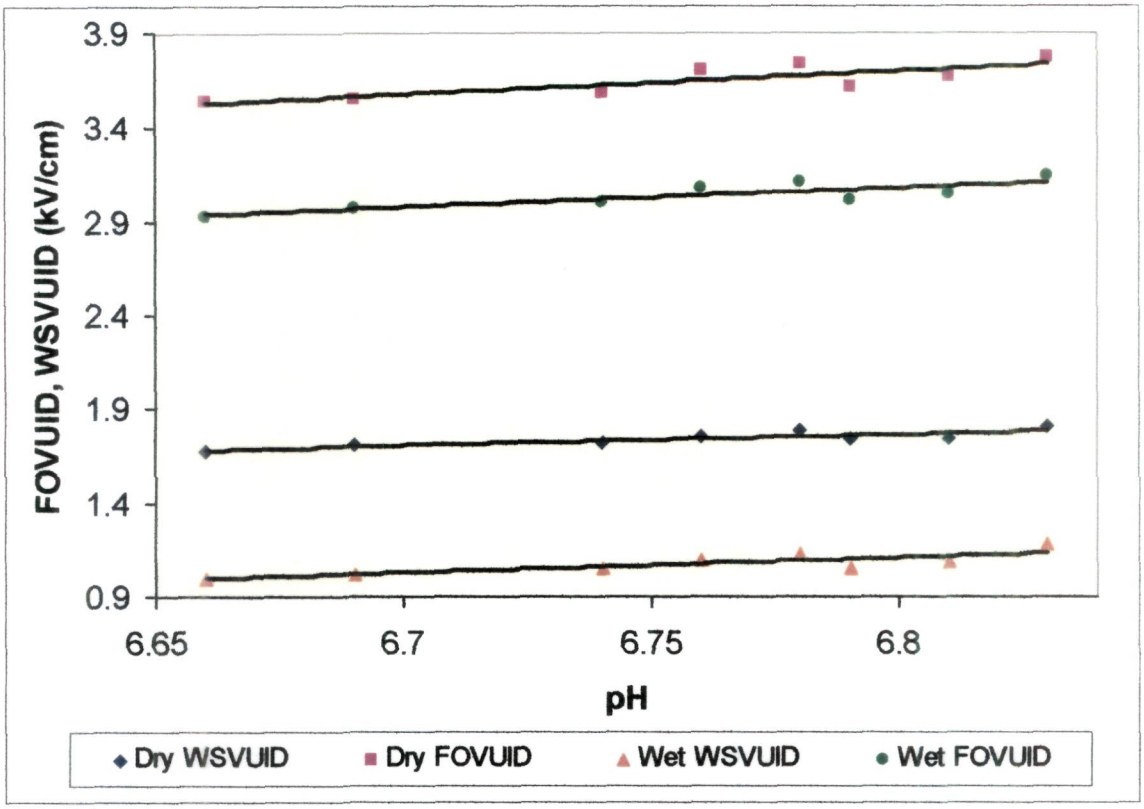


Fig.4.35: FOVUID, WSVUID vs pH Curve for Thermal Plant March 2006

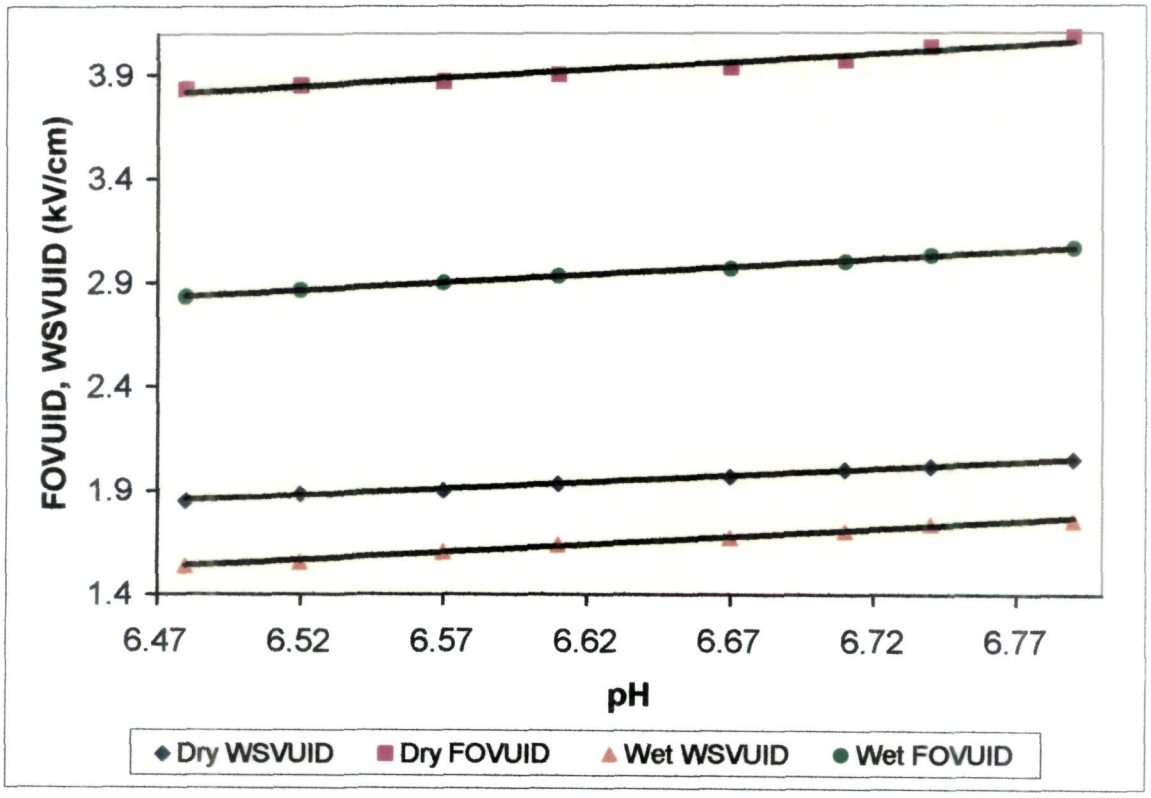


Fig.4.36: FOVUID, WSVUID vs pH Curve for Thermal Plant July 2006

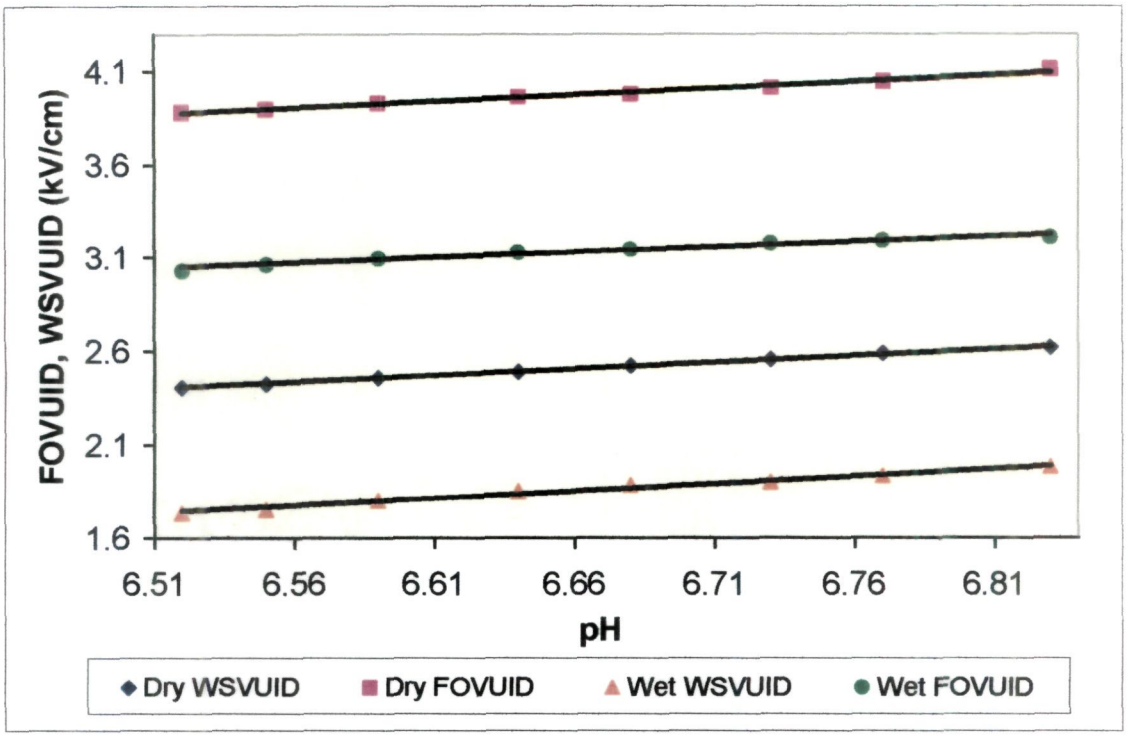


Fig. 4.37: FOVUID, WSVUID vs pH Curve for Thermal Plant Dec 2006

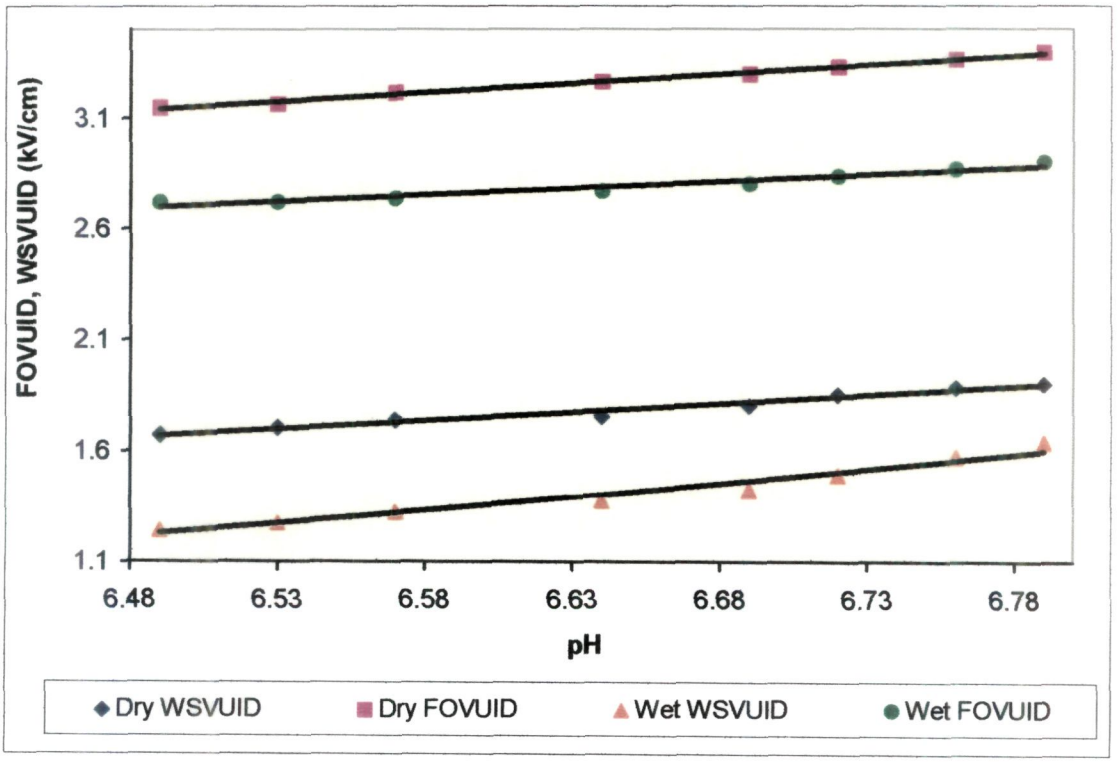


Fig. 4.38: FOVUID, WSVUID vs pH Curve for Thermal Plant Dec 2007

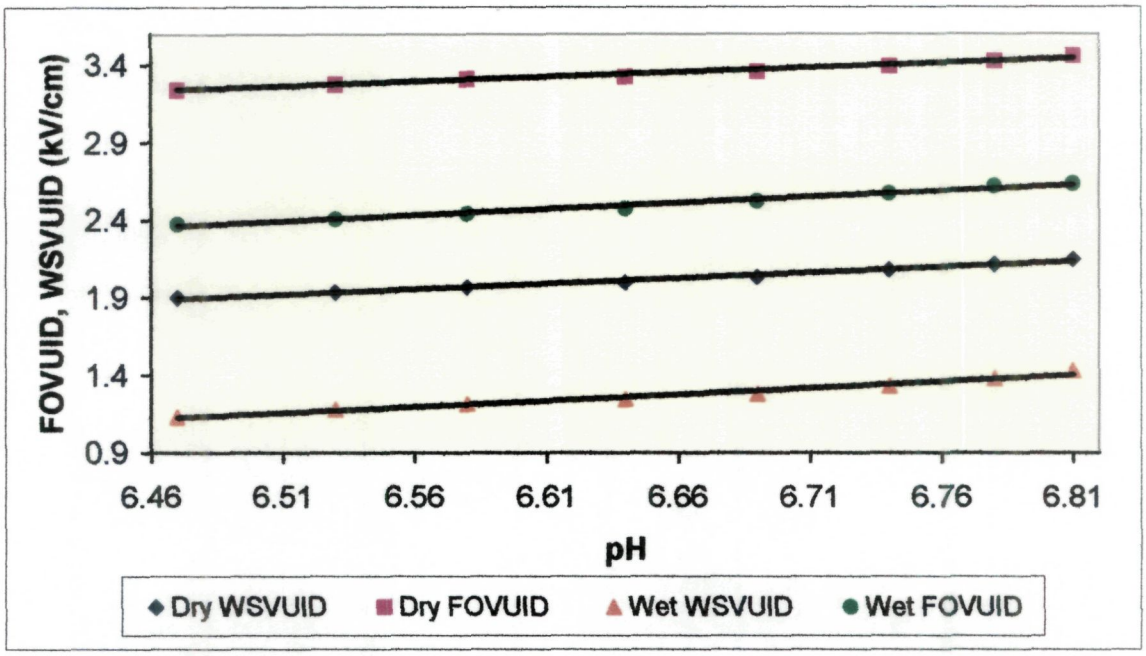


Fig. 4.39: FOVUID, WSVUID vs pH Curve for Thermal Plant March 2008

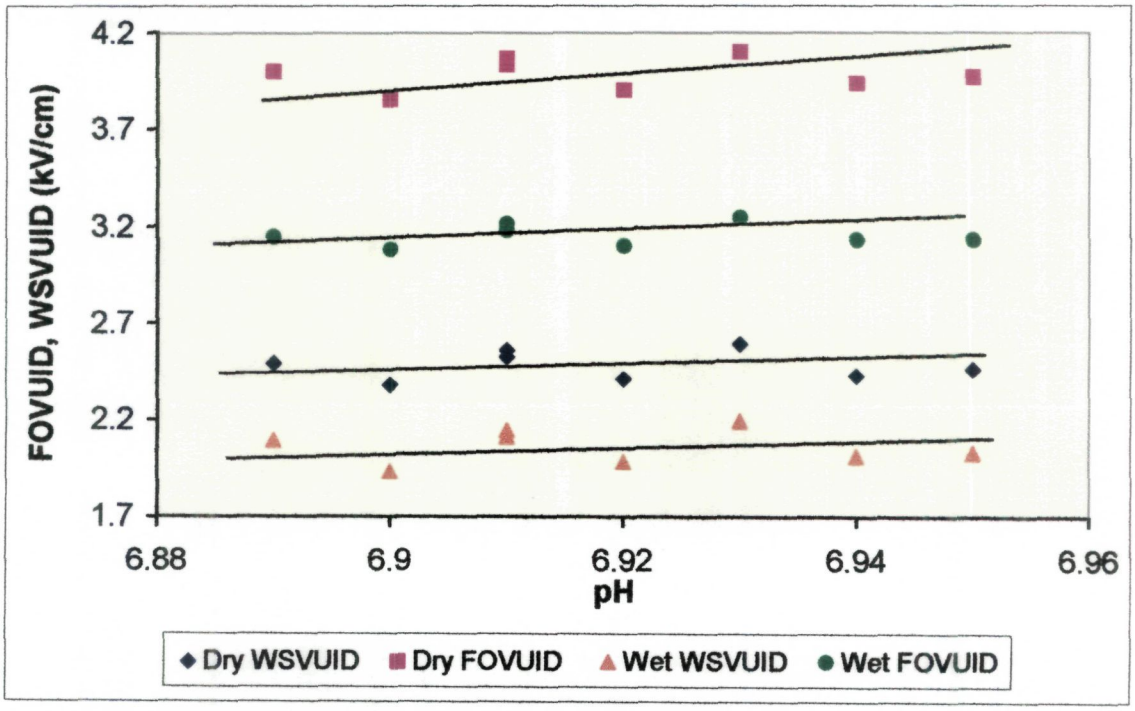


Fig. 4.40: FOVUID, WSVUID vs pH Curve for Nishat Apartment Dec 2005

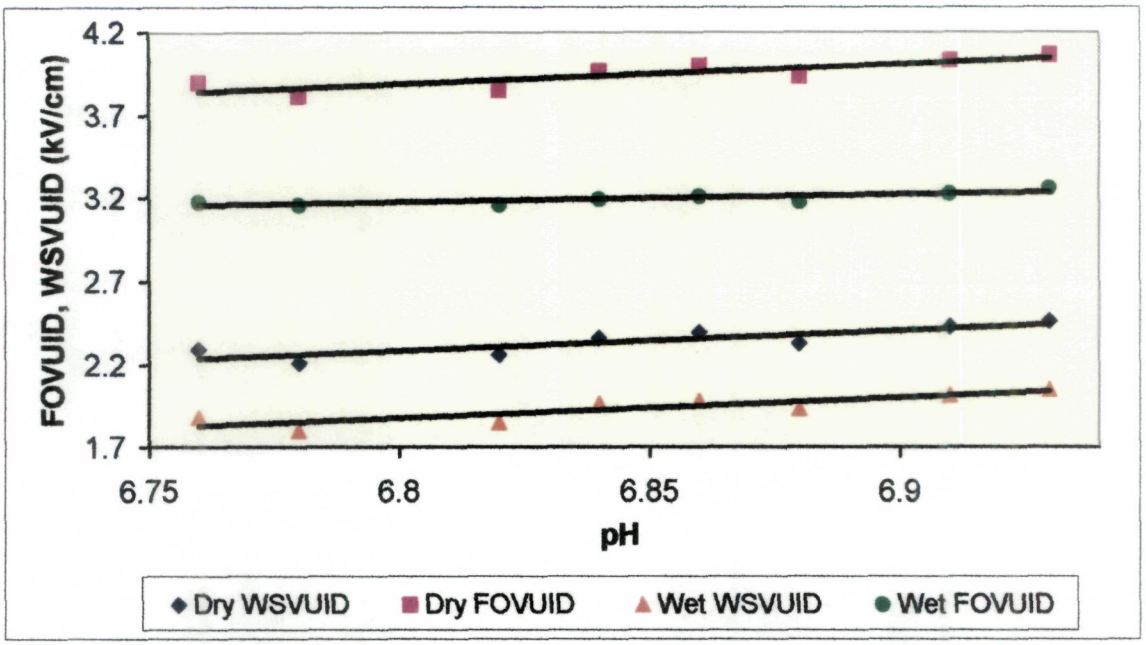


Fig. 4.41: FOVUID, WSVUID vs pH Curve for Nishat Apartment March 2006

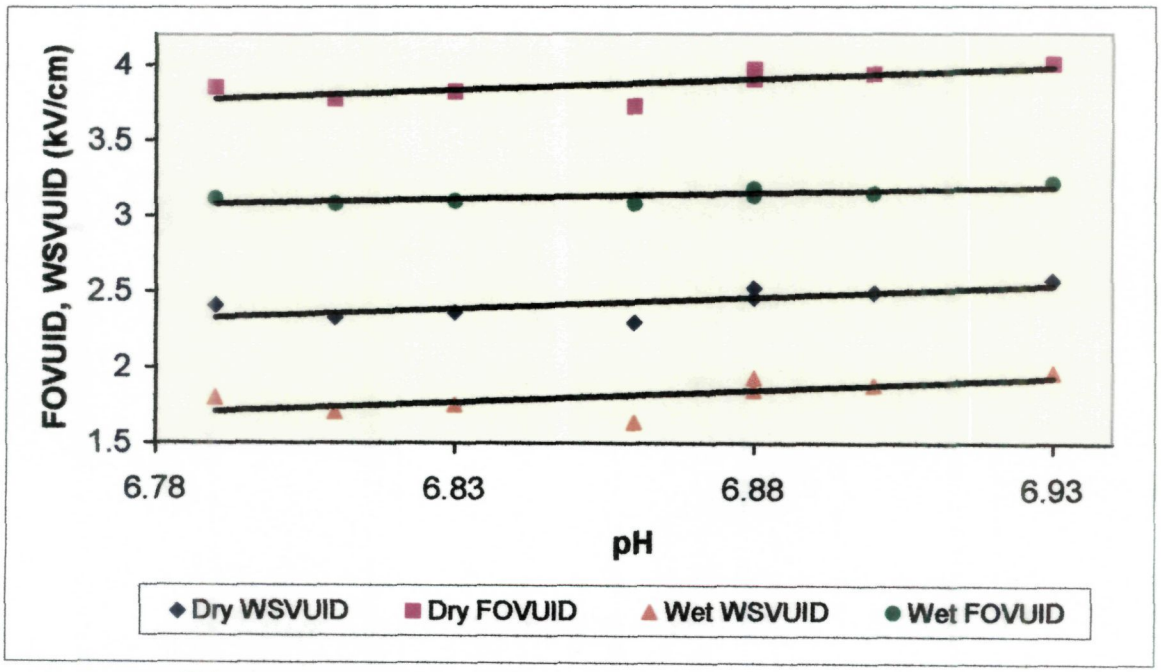


Fig. 4.42: FOVUID, WSVUID vs pH Curve for Nishat Apartment July 2006

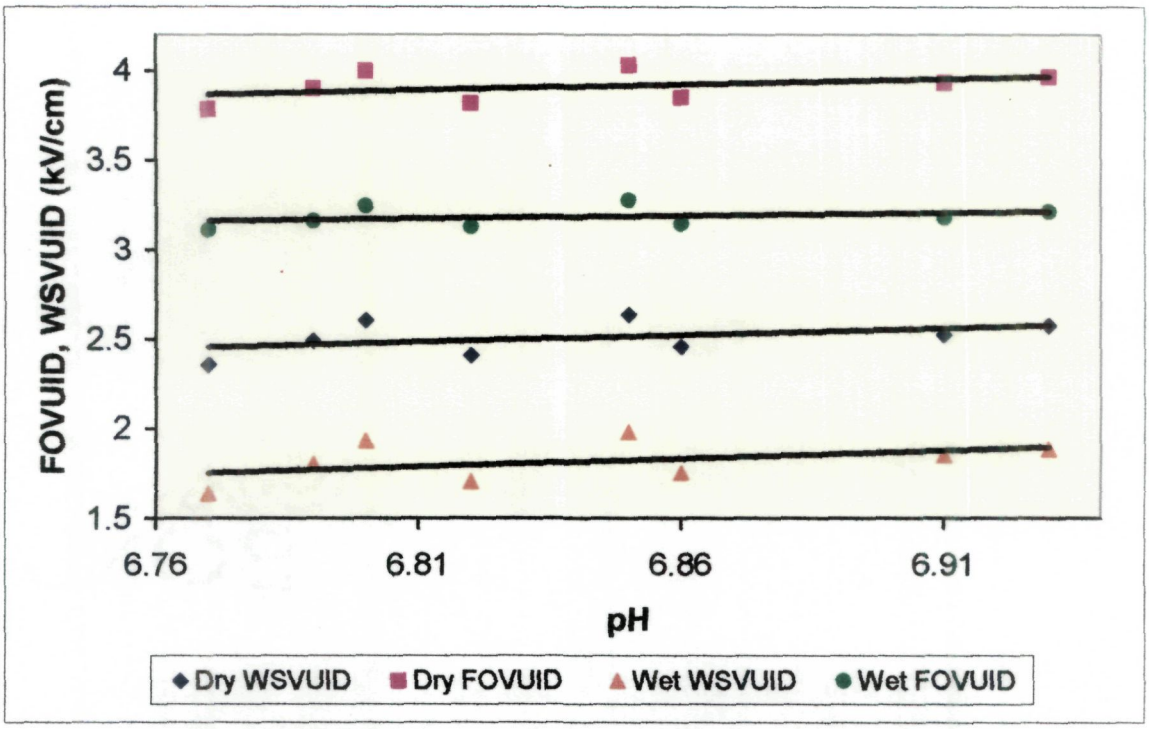


Fig. 4.43: FOVUID, WSVUID vs pH Curve for Nishat Apartment Dec 2006

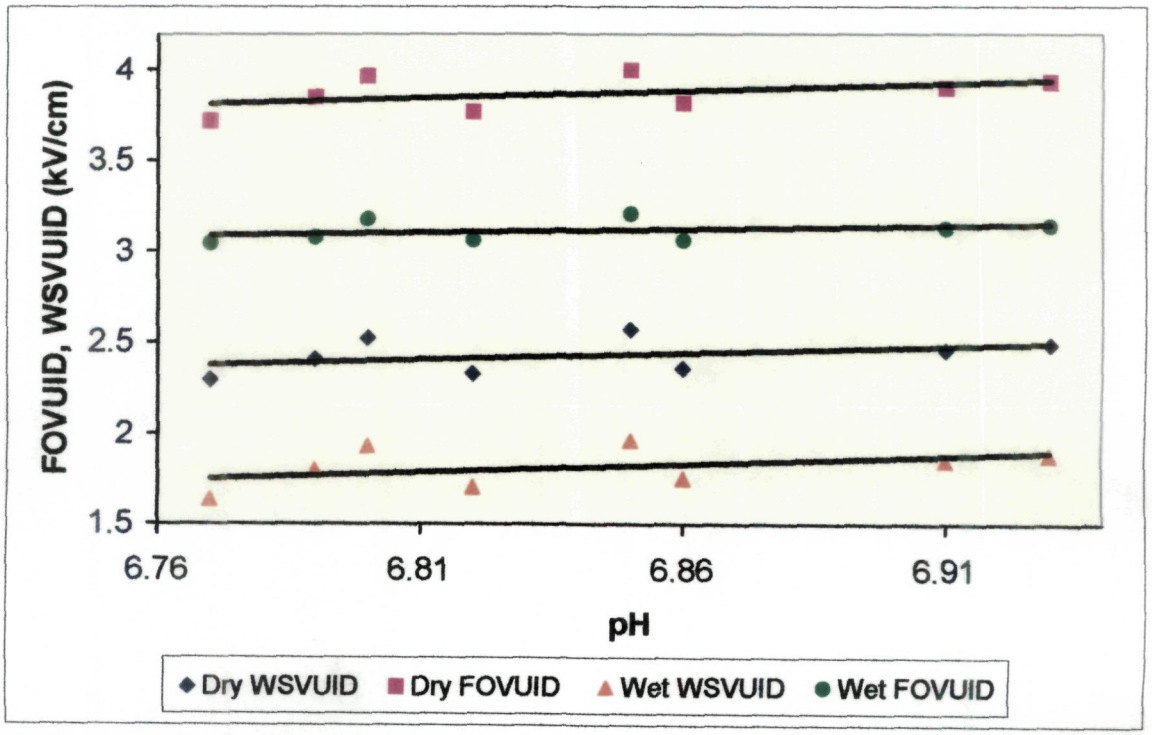


Fig. 4.44: FOVUID, WSVUID vs pH Curve for Nishat Apartment Dec 2007

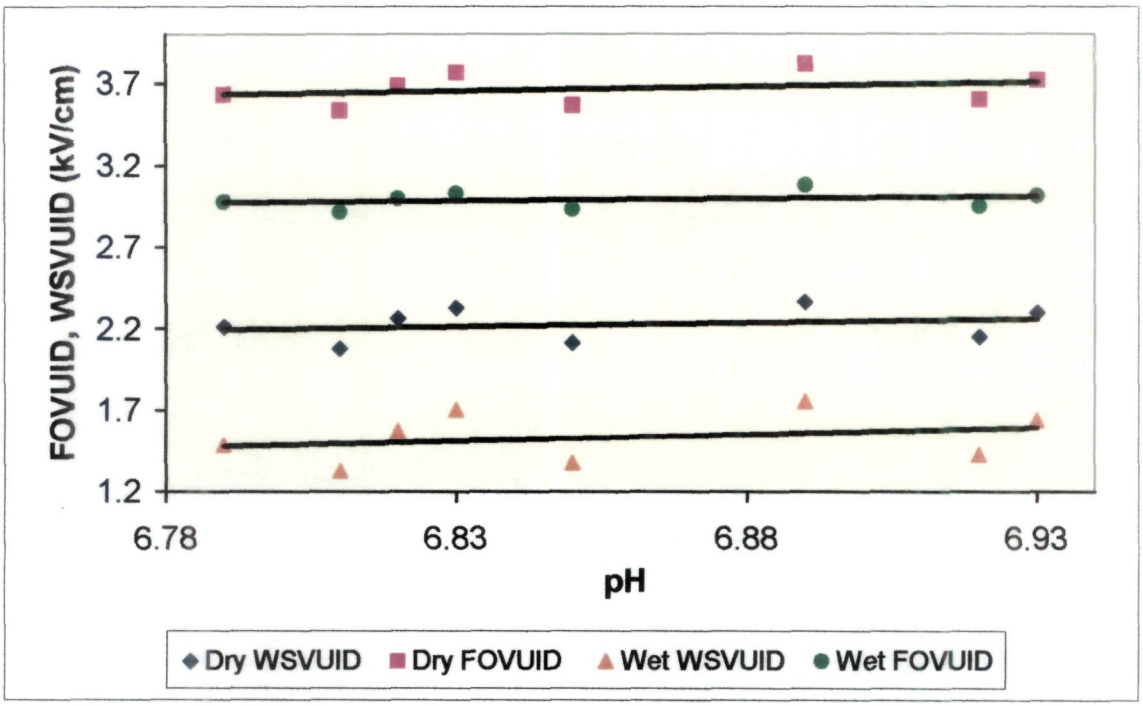


Fig. 4.45: FOVUID, WSVUID vs pH Curve for Nishat Apartment March 2008

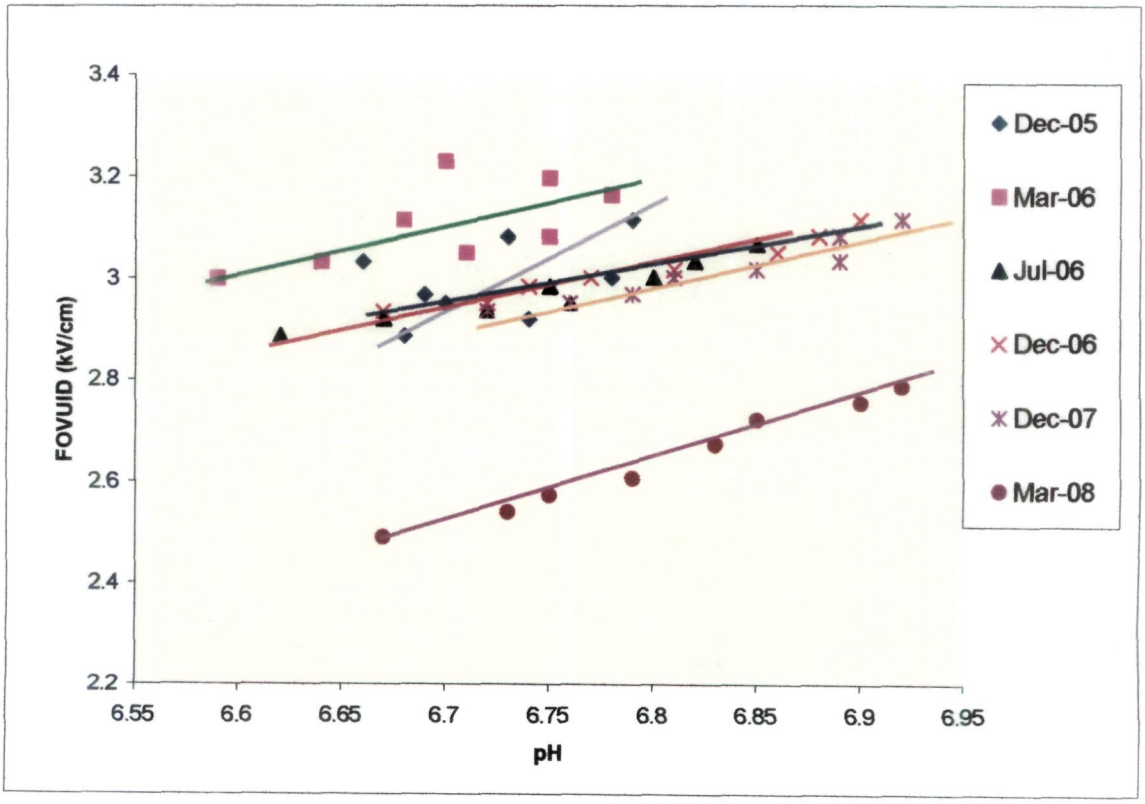


Fig. 4.46: Comparative graph FOVUID vs pH for NH-91

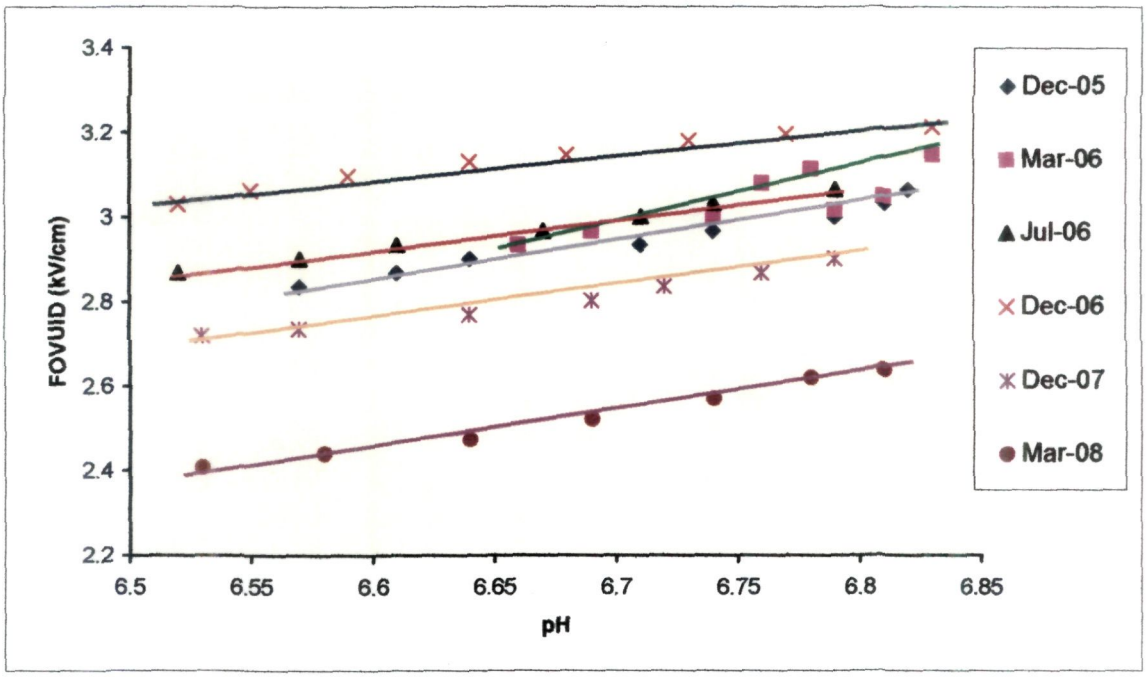


Fig. 4.47: Comparative graph FOVUID vs pH for Thermal Plant

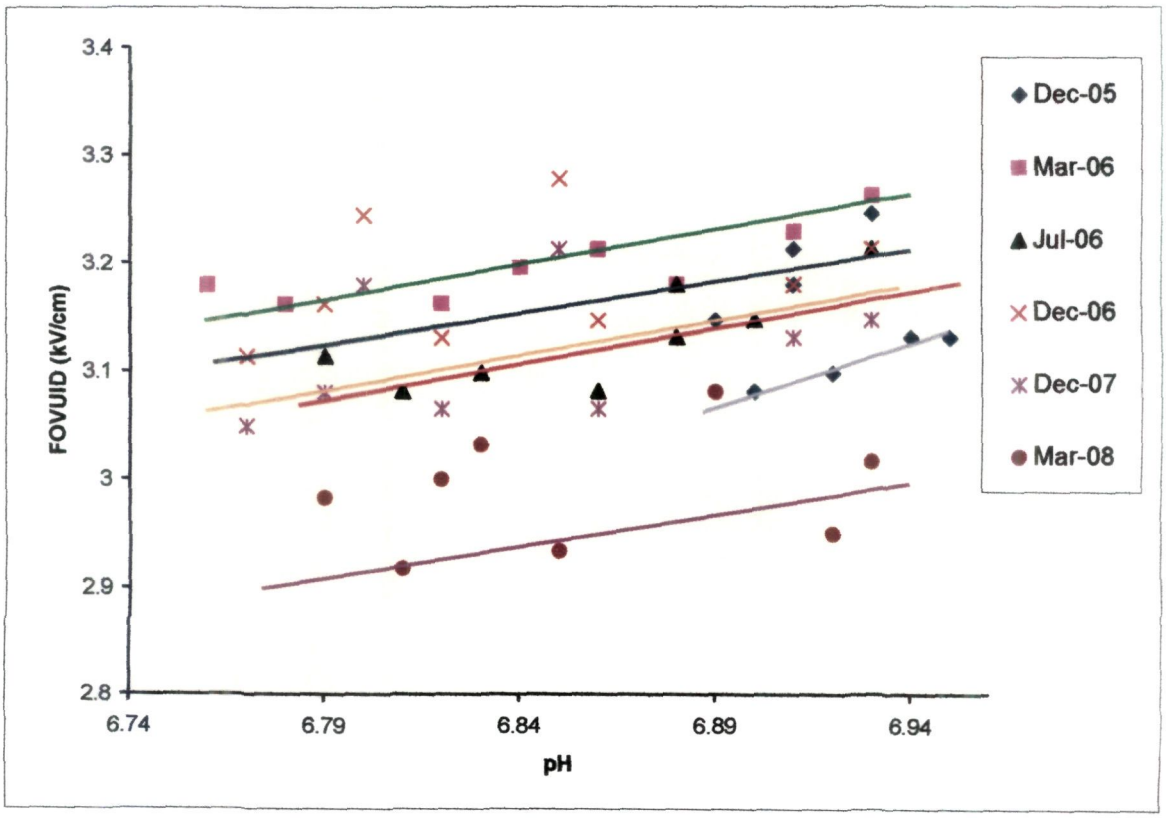


Fig. 4.48: Comparative graph FOVUID vs pH for Nishat Apartment

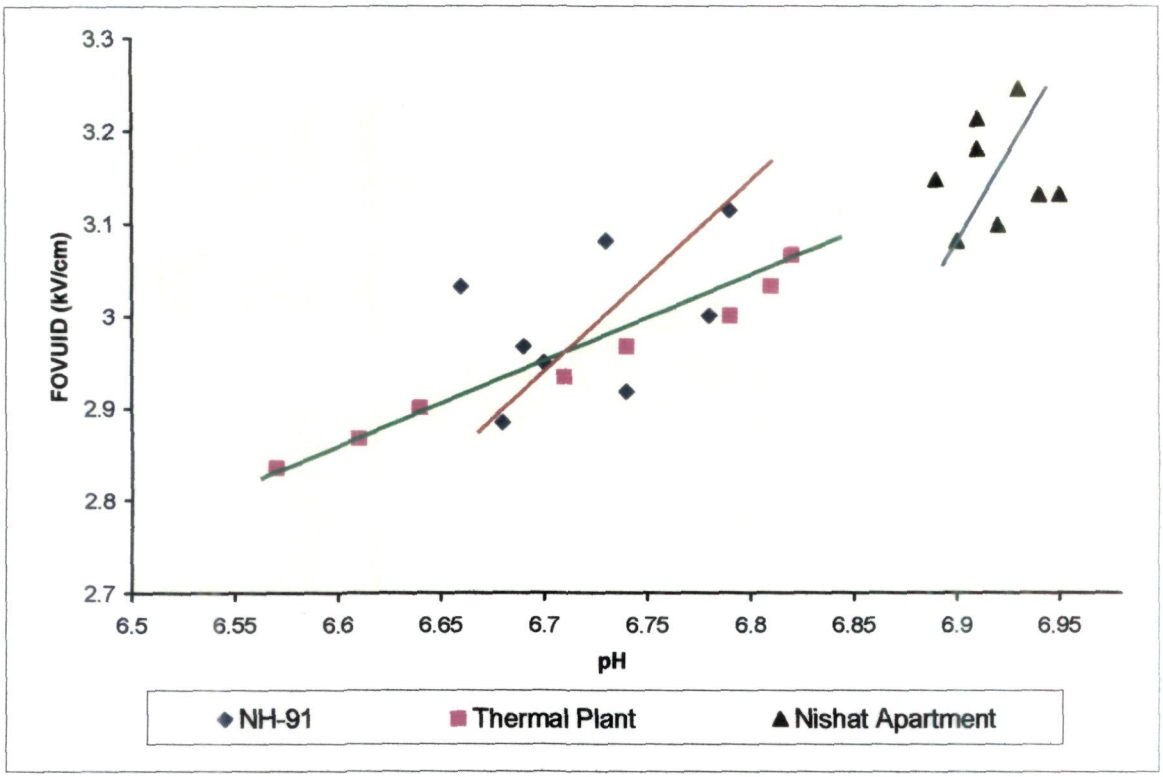


Fig. 4.49: Comparative graph FOVUID vs pH for the three sites Dec. 2005.

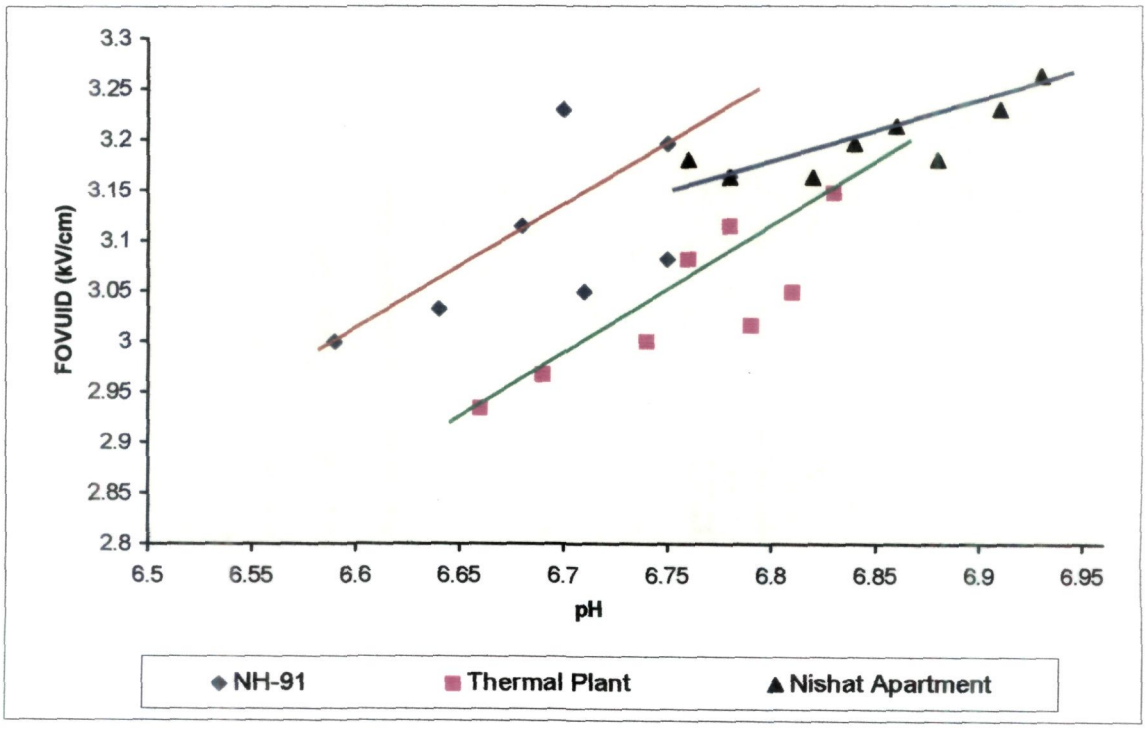


Fig. 4.50: Comparative graph FOVUID vs pH for the three sites March 2006.

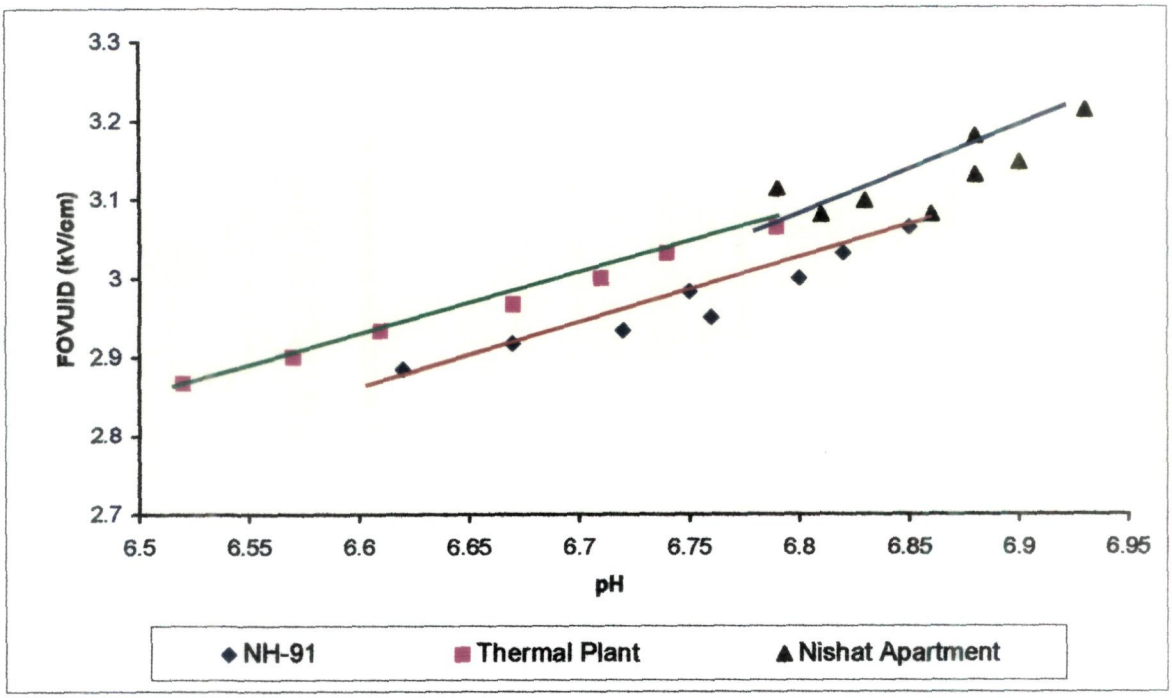


Fig. 4.51: Comparative graph FOVUID vs ESDD for the three sites July 2006.

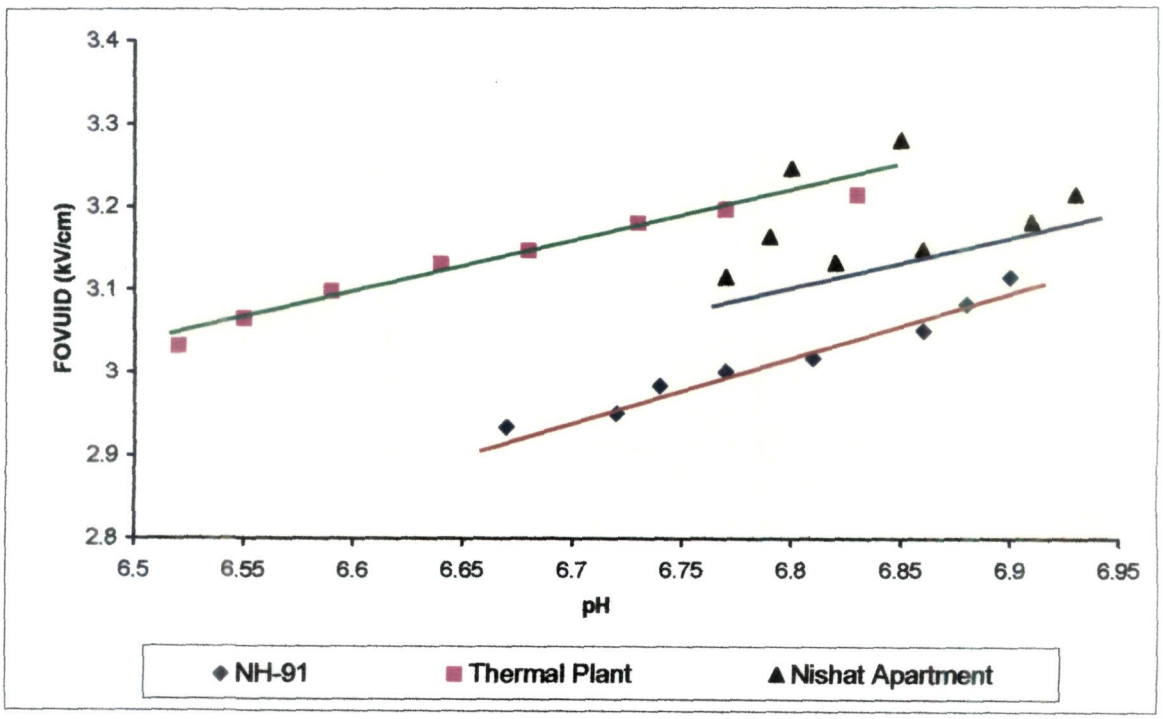


Fig. 4.52: Comparative graph FOVUID vs pH for the three sites Dec. 2006.

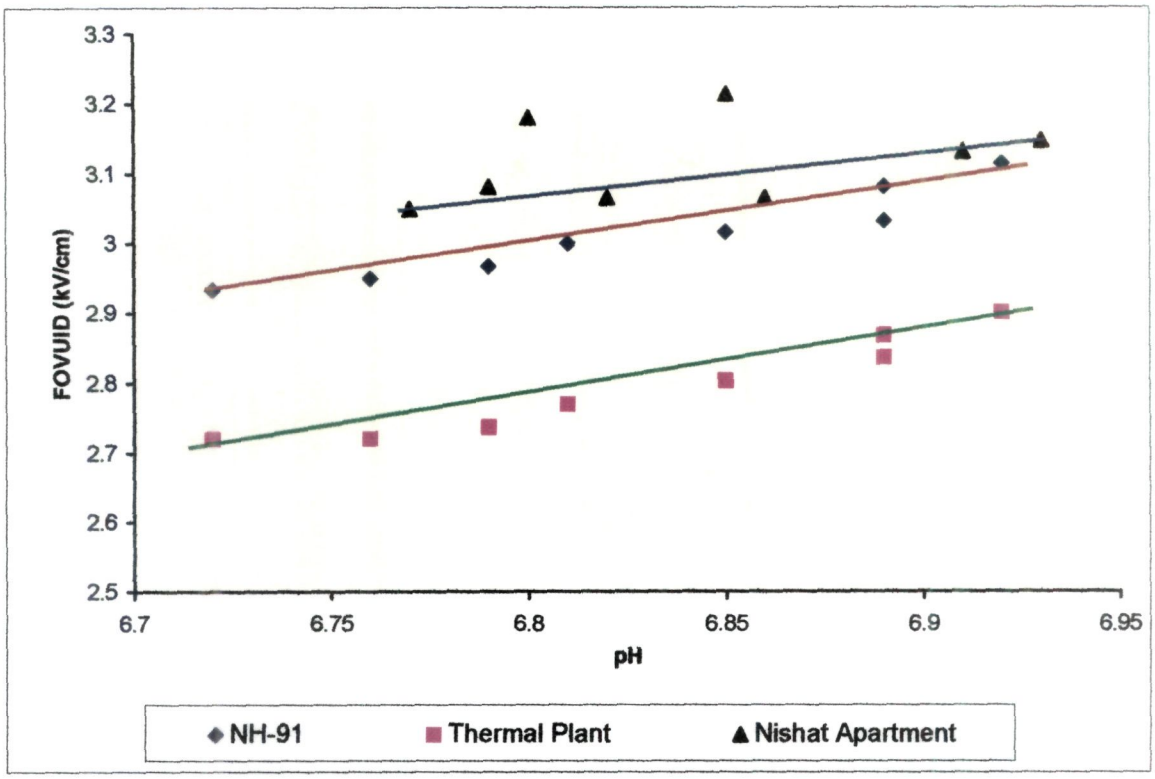


Fig. 4.53: Comparative graph FOVUID vs pH for the three sites Dec. 2007.

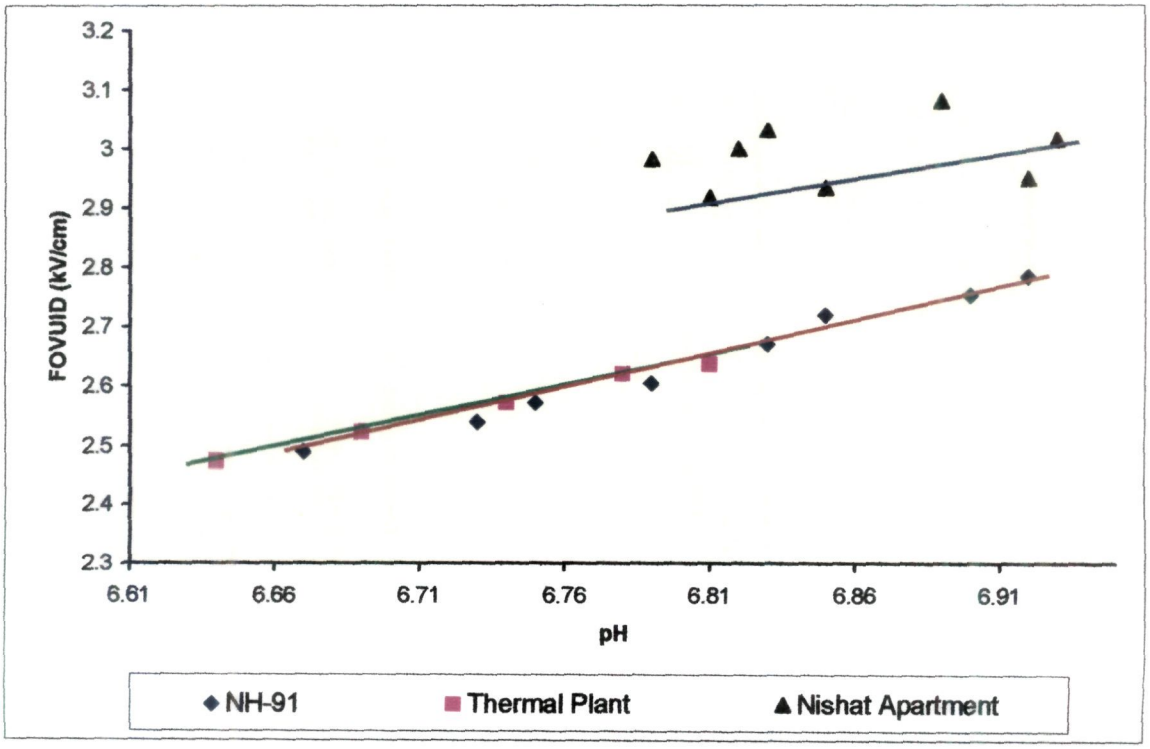


Fig. 4.54: Comparative graph FOVUID vs pH for the three sites March 2008.

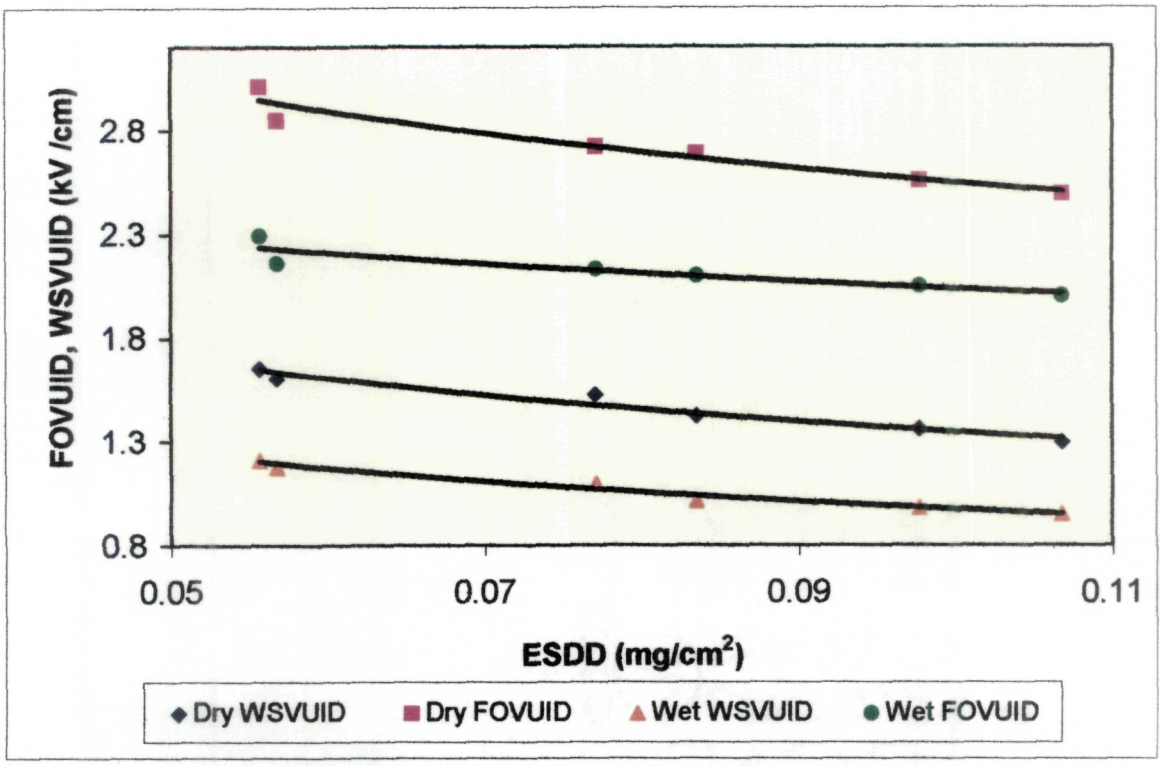


Fig. 4.55: FOVUID, WSVUID vs ESDD Curve for NaCl

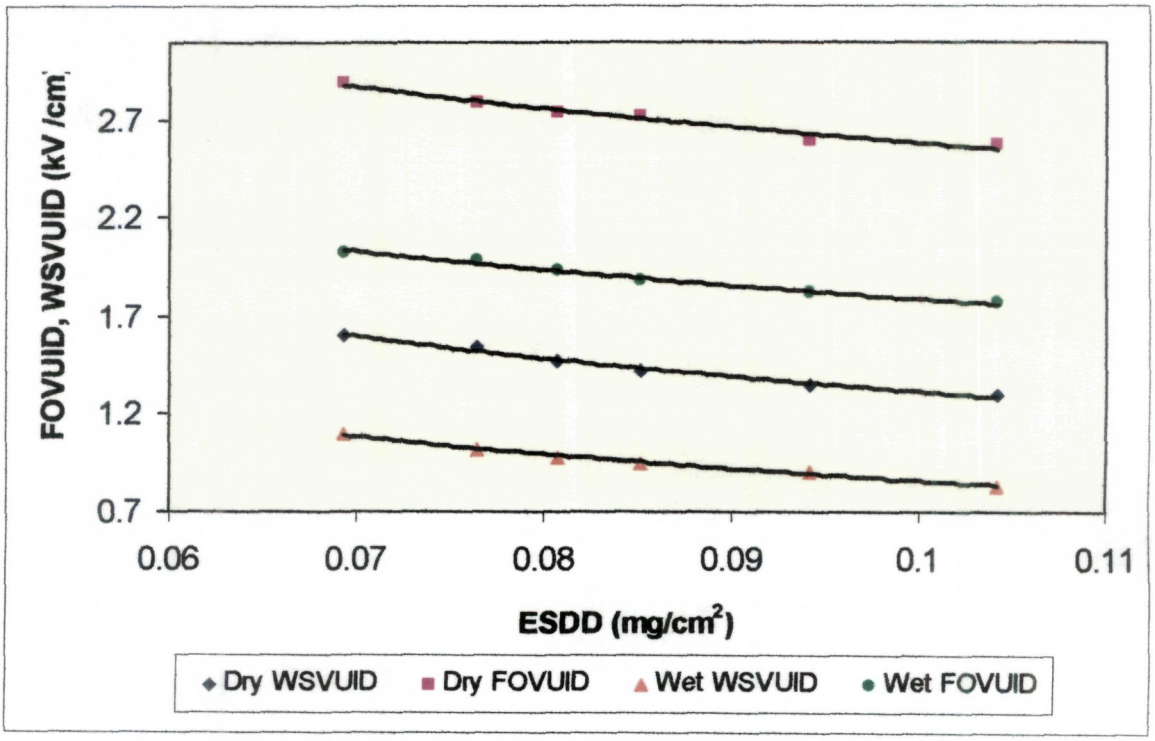


Fig. 4.56: FOVUID, WSVUID vs ESDD Curve for NaCl

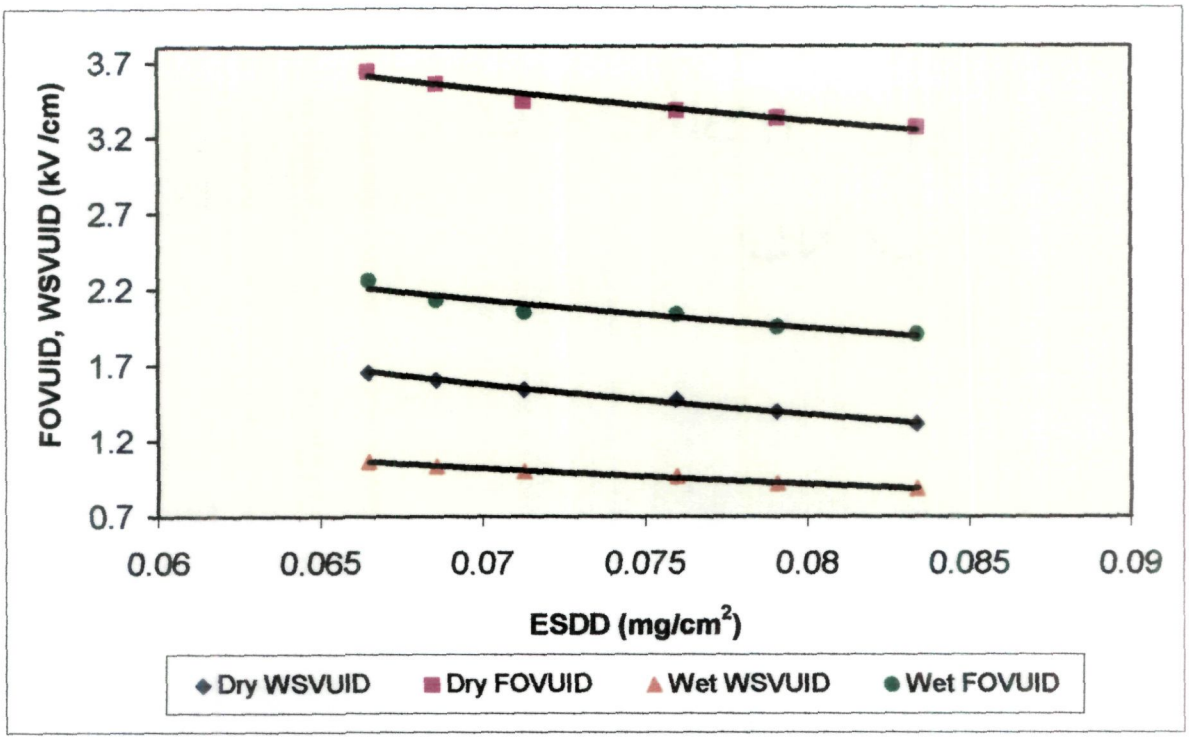


Fig. 4.57: FOVUID, WSVUID vs ESDD Curve for KCl

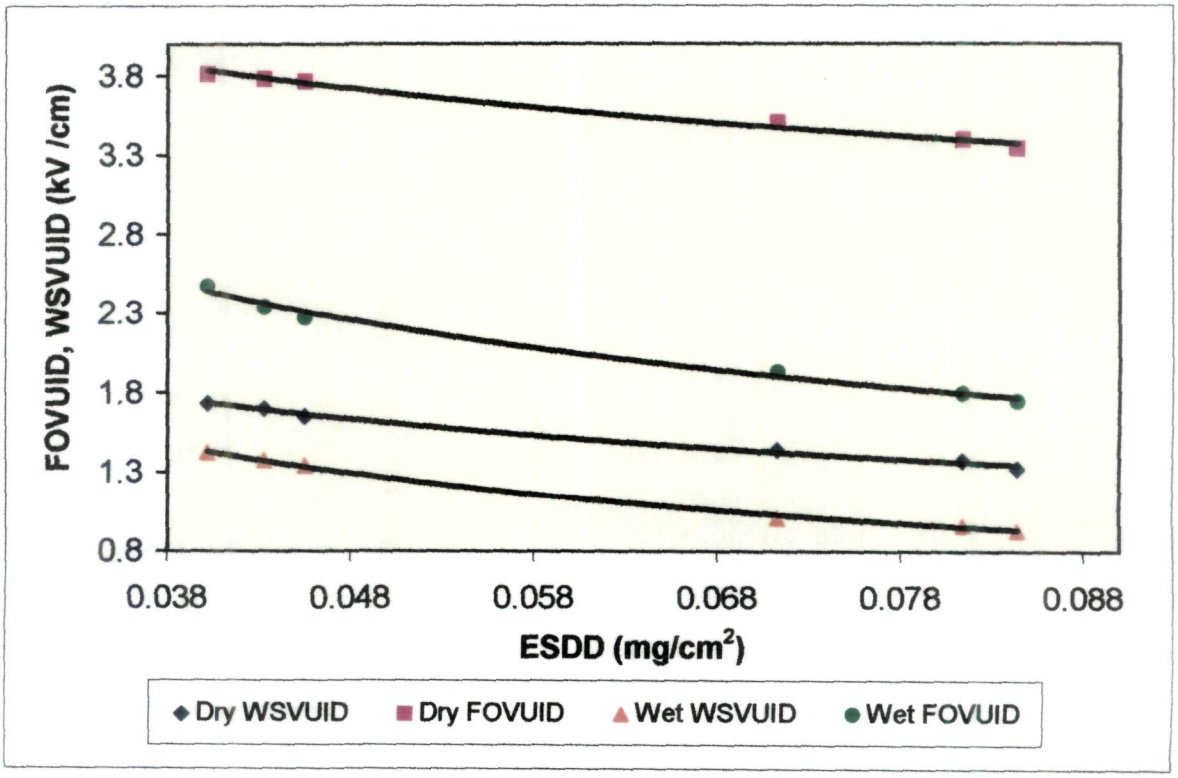


Fig. 4.58: FOVUID, WSVUID vs ESDD Curve for KCl

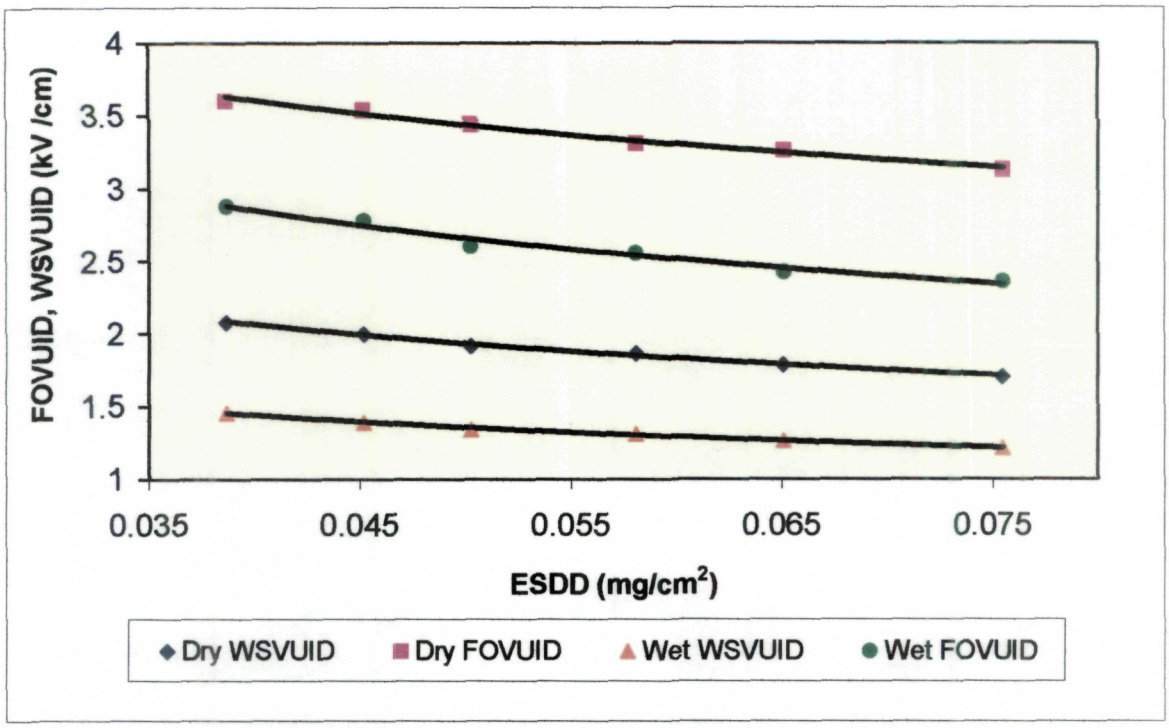


Fig. 4.59: FOVUID, WSVUID vs ESDD Curve for $CaCl_2$

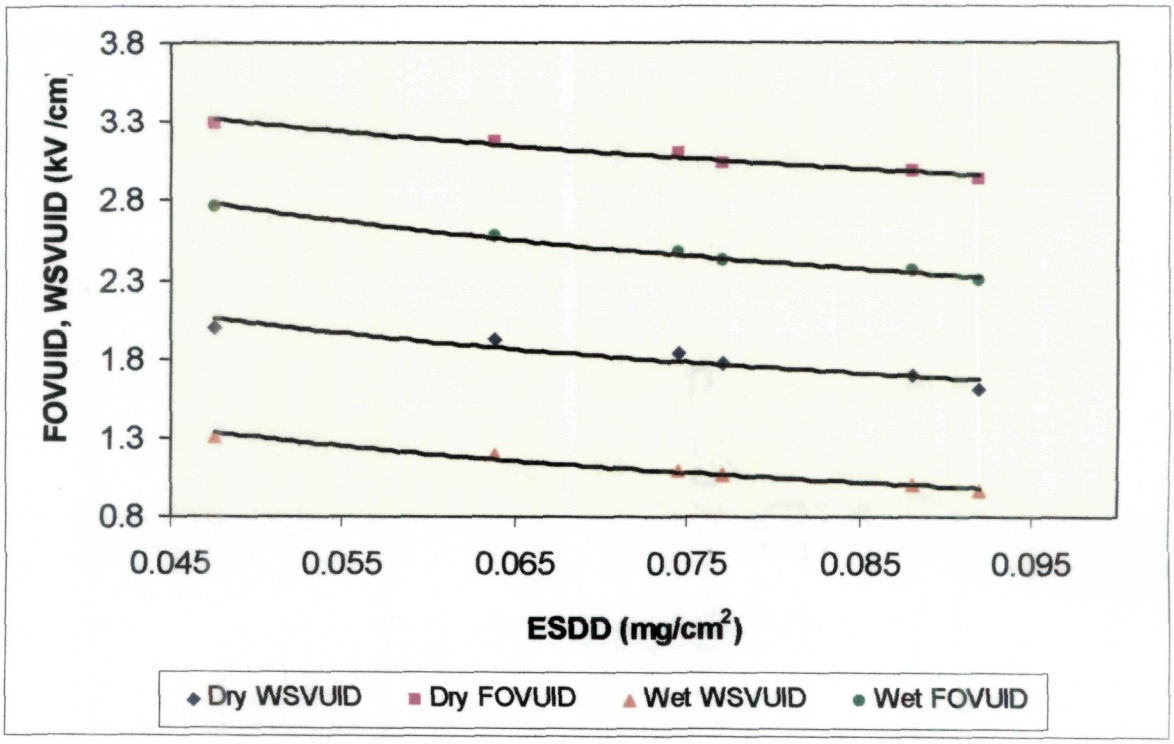


Fig. 4.60: FOVUID, WSVUID vs ESDD Curve for $CaCl_2$

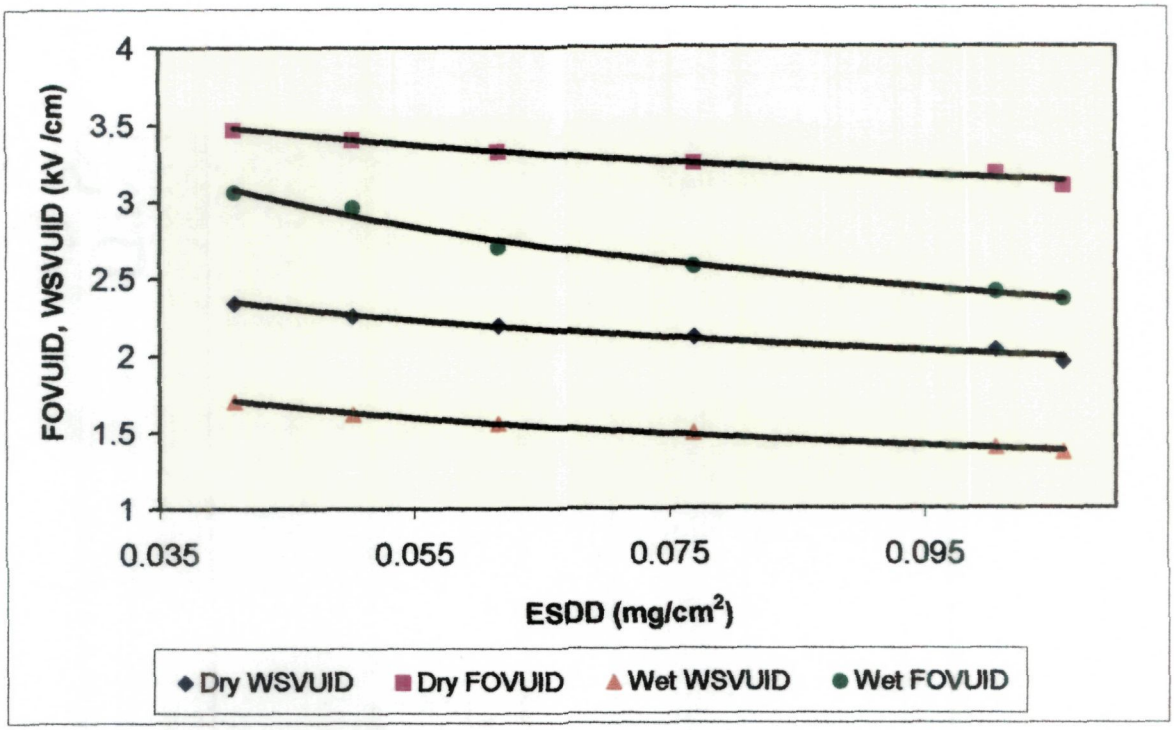


Fig. 4.61: FOVUID, WSVUID vs ESDD Curve for Na_2SO_4

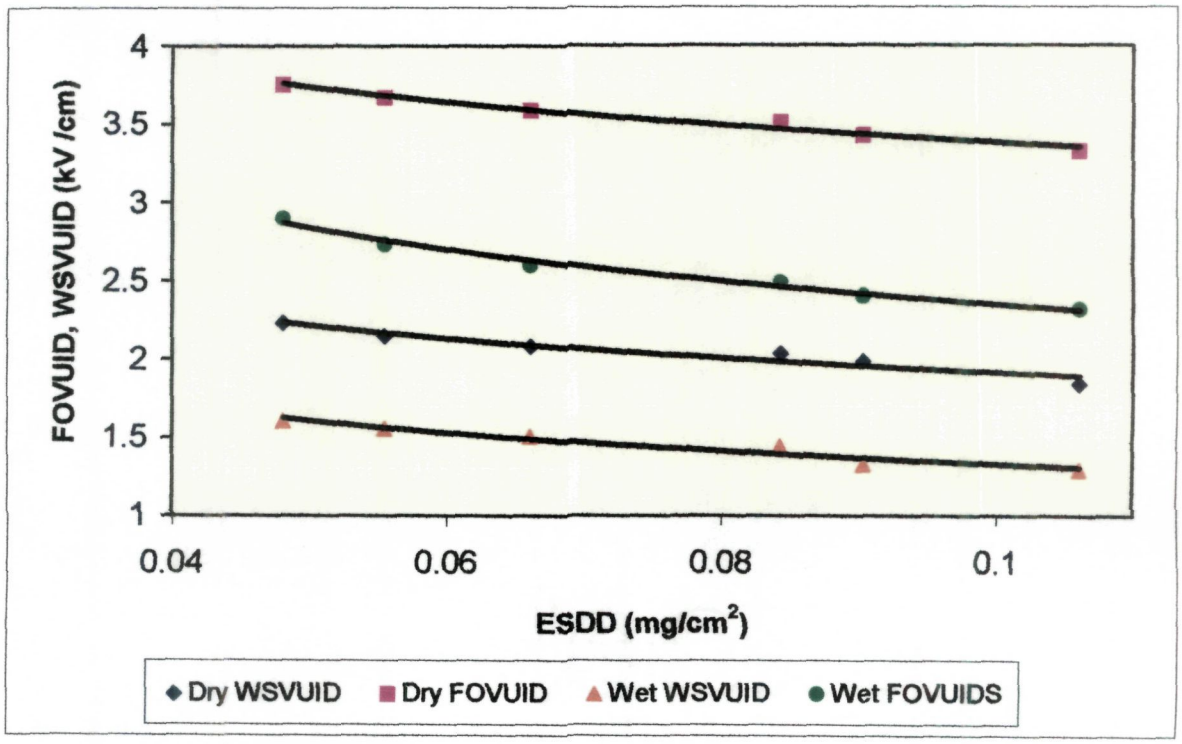


Fig. 4.62: FOVUID, WSVUID vs ESDD Curve for Na_2SO_4

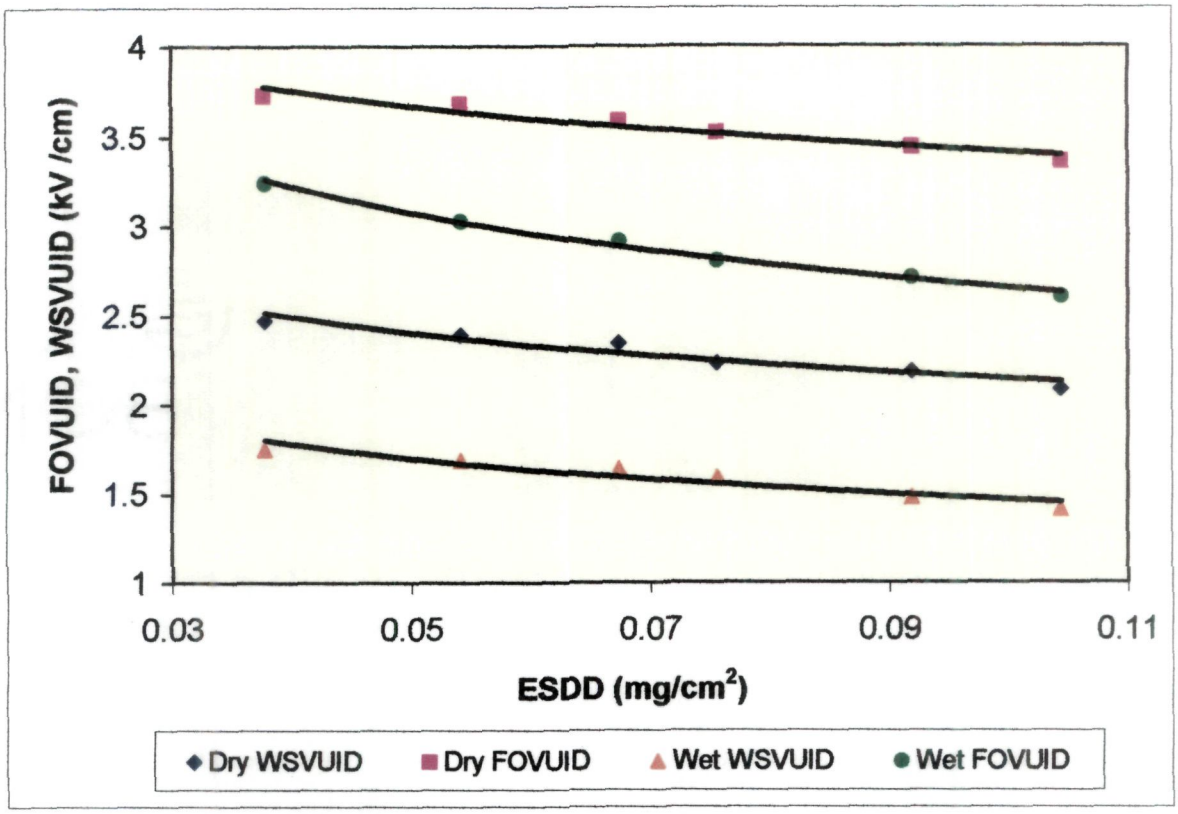


Fig. 4.63: FOVUID, WSVUID vs ESDD Curve for $MgSO_4$

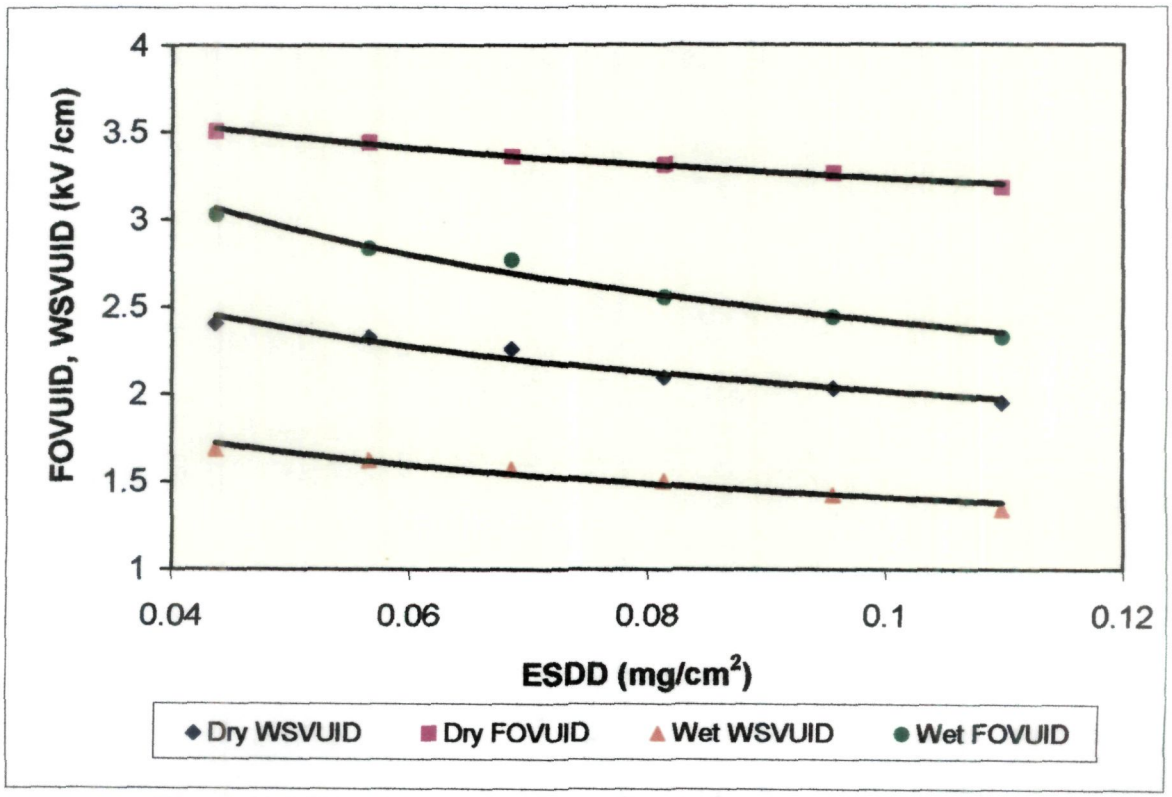


Fig. 4.64: FOVUID, WSVUID vs ESDD Curve for $MgSO_4$

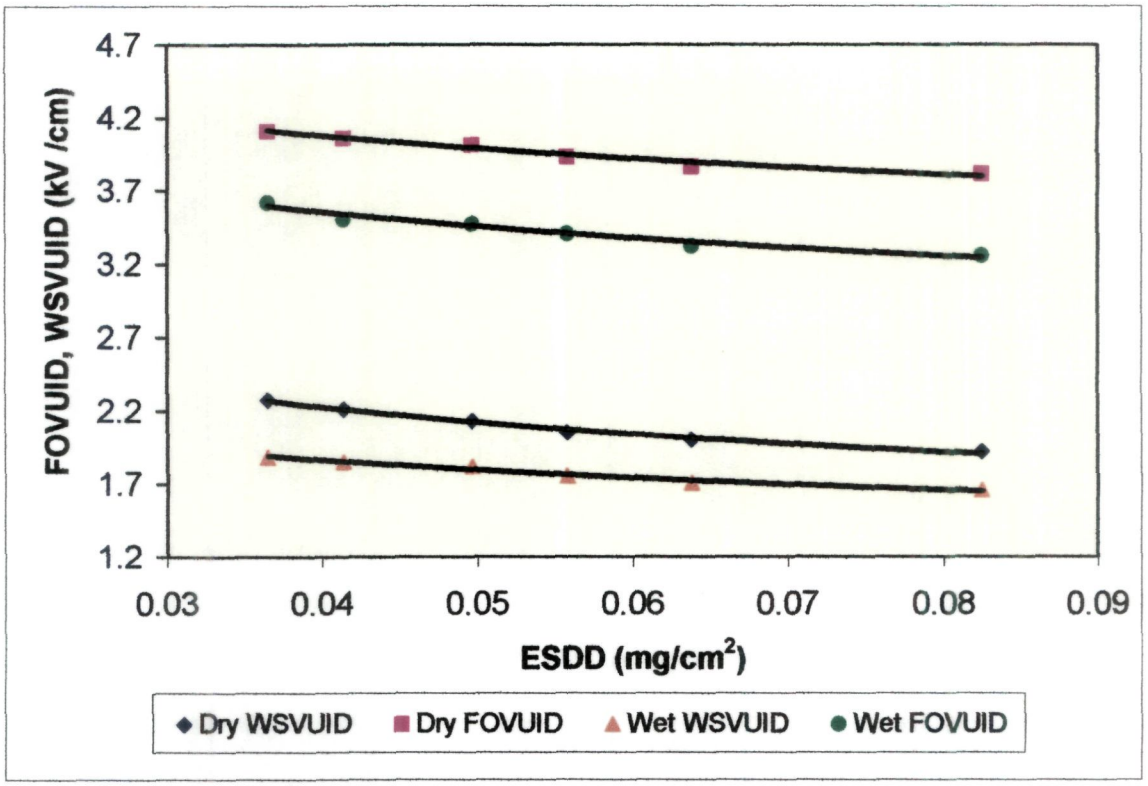


Fig. 4.65: FOVUID, WSVUID vs ESDD Curve for $CaSO_4$

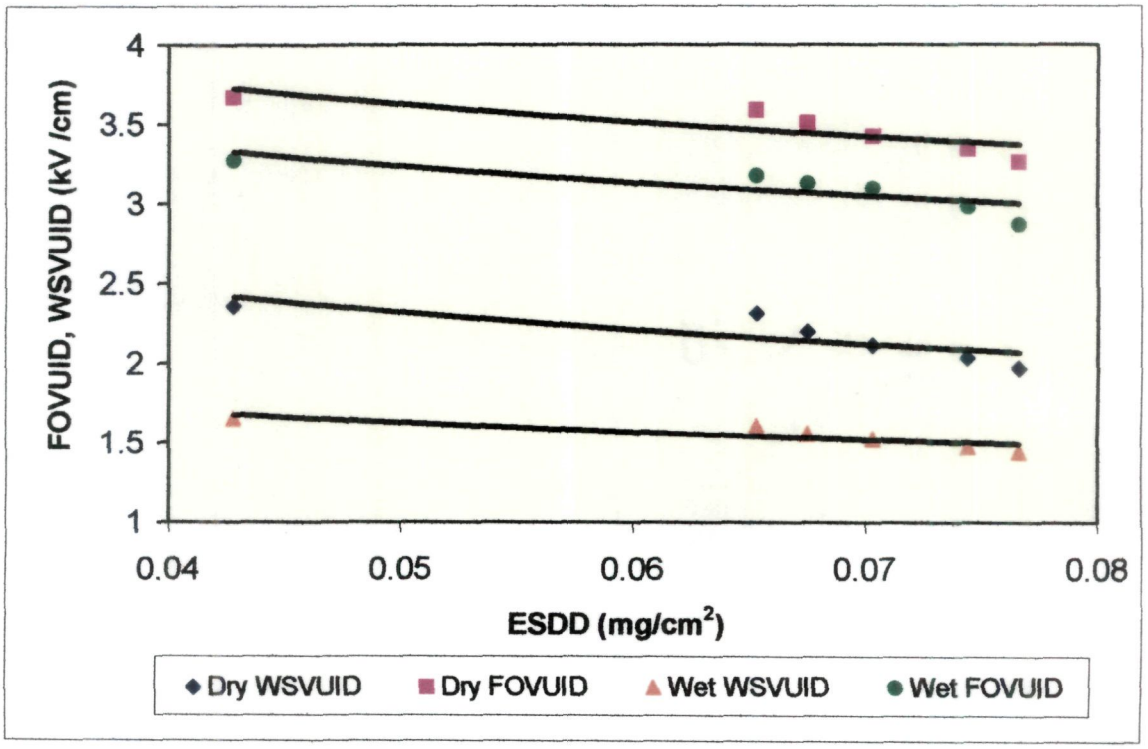


Fig. 4.66: FOVUID, WSVUID vs ESDD Curve for $CaSO_4$

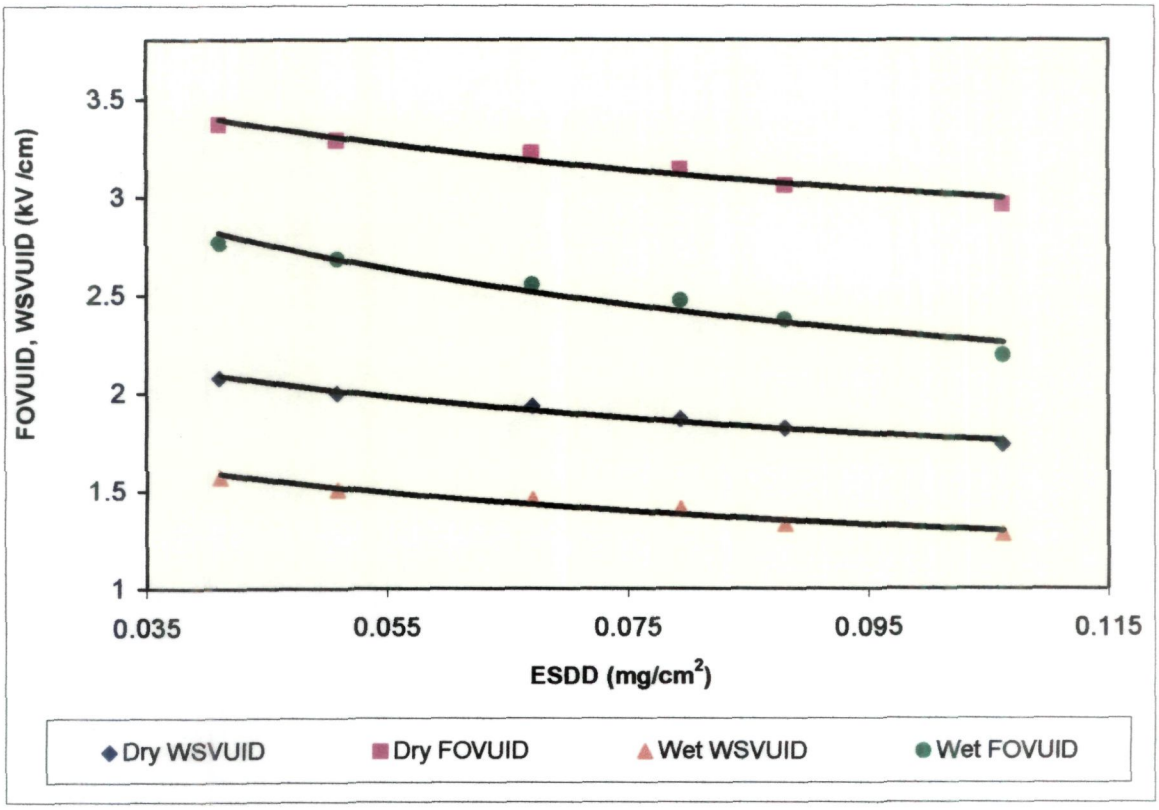


Fig. 4.67: FOVUID, WSVUID vs ESDD Curve for $NaNO_3$

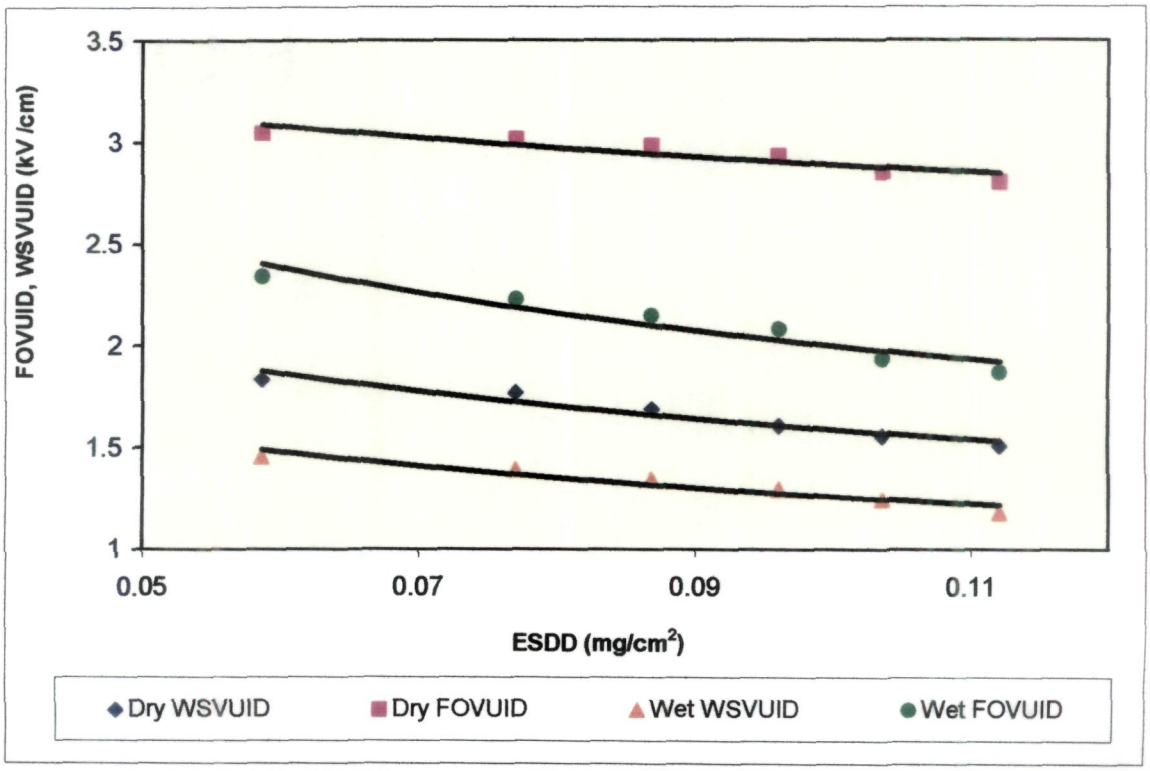


Fig. 4.68: FOVUID, WSVUID vs ESDD Curve for $NaNO_3$

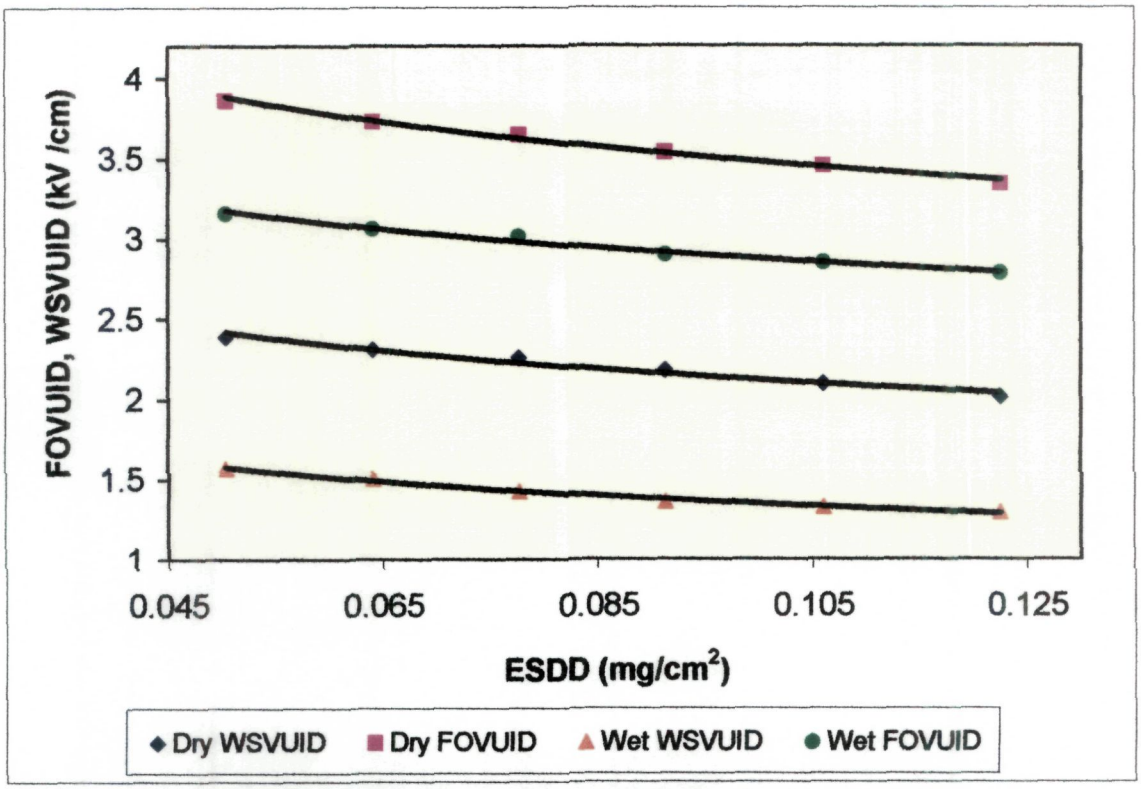


Fig. 4.69: FOVUID, WSVUID vs ESDD Curve for Ca $(NO_3)_2$

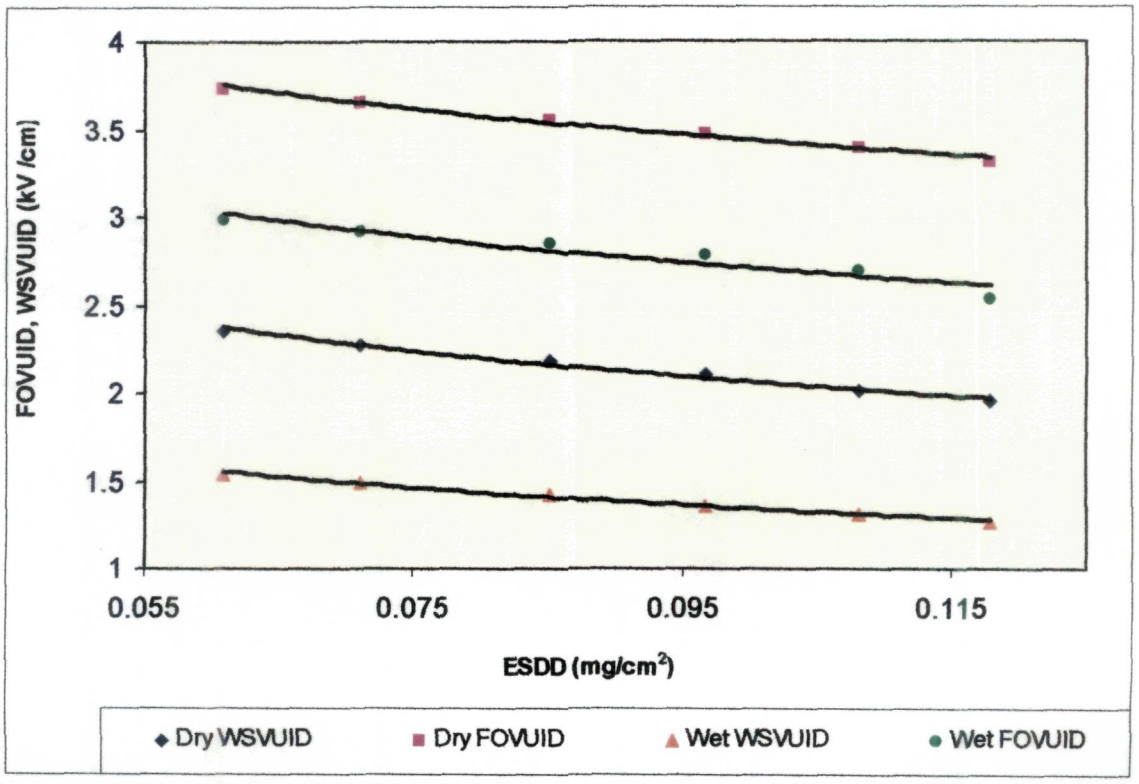


Fig. 4.70: FOVUID, WSVUID vs ESDD Curve for Ca $(NO_3)_2$

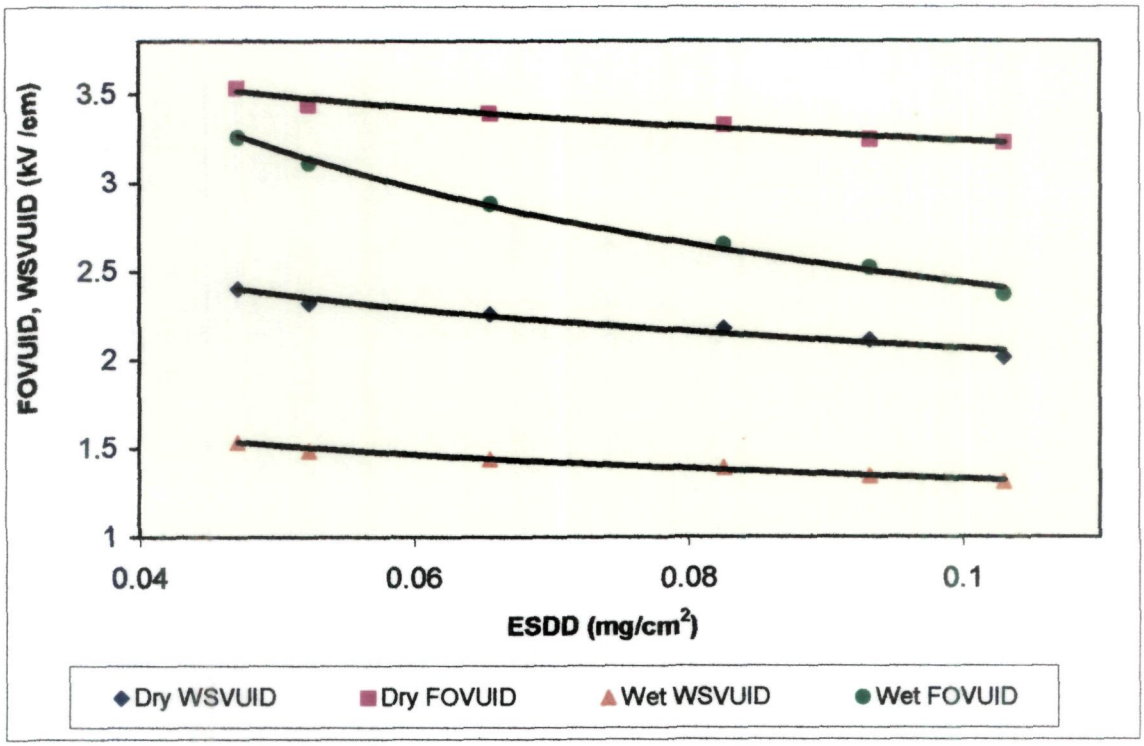


Fig. 4.71: FOVUID, WSVUID vs ESDD Curve for Mg $(NO_3)_2$

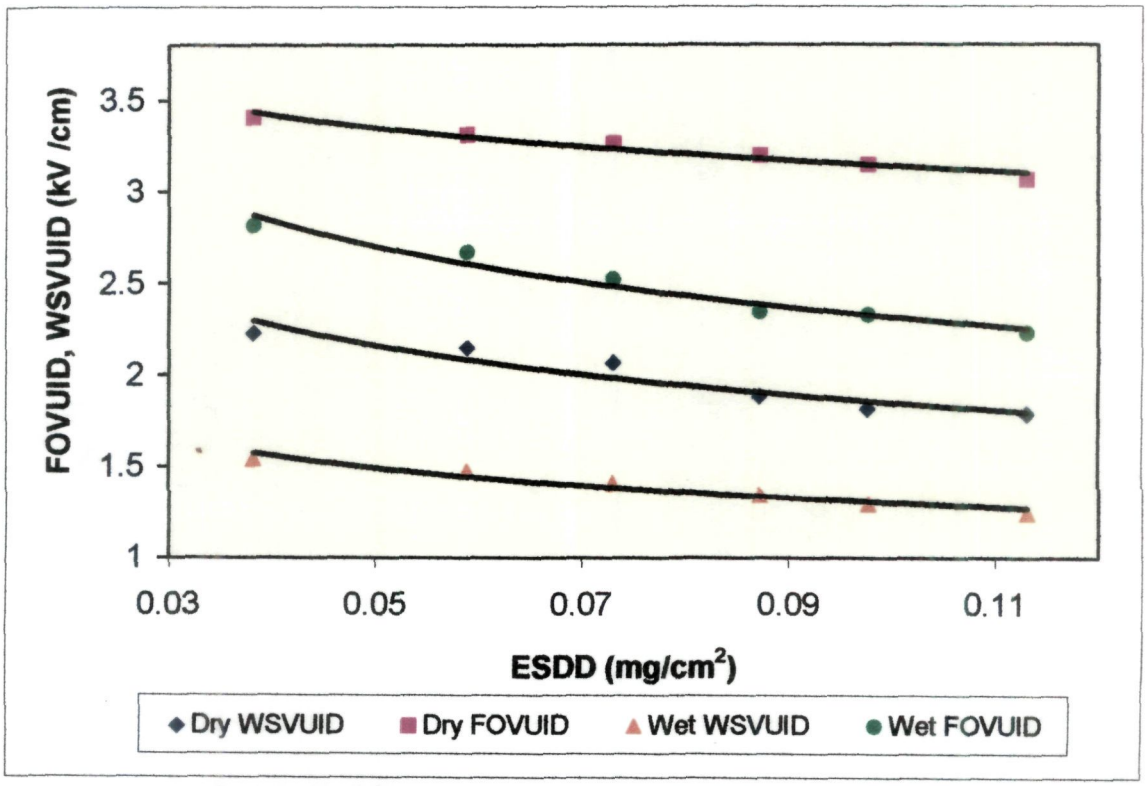


Fig. 4.72: FOVUID, WSVUID vs ESDD Curve for Mg $(NO_3)_2$

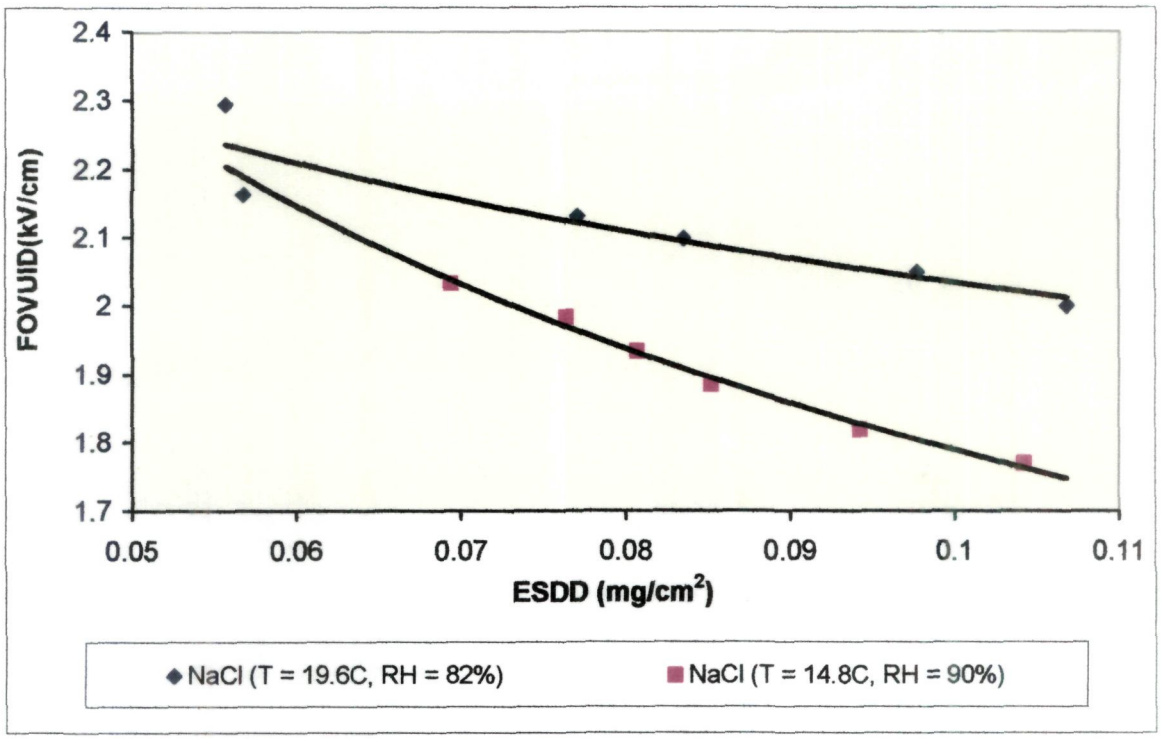


Fig. 4.73: FOVUID vs ESDD Curve for NaCl at different temperature and relative humidity.

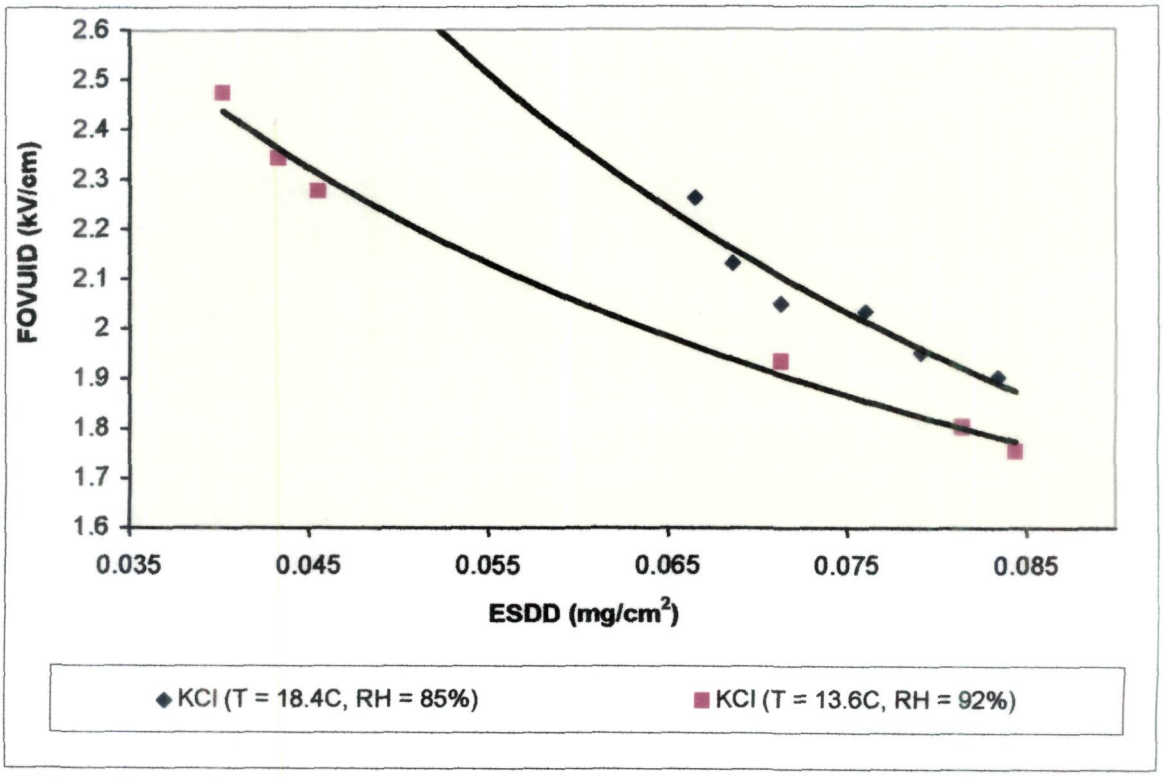


Fig. 4.74: FOVUID vs ESDD Curve for KCl at different temperature and relative humidity.

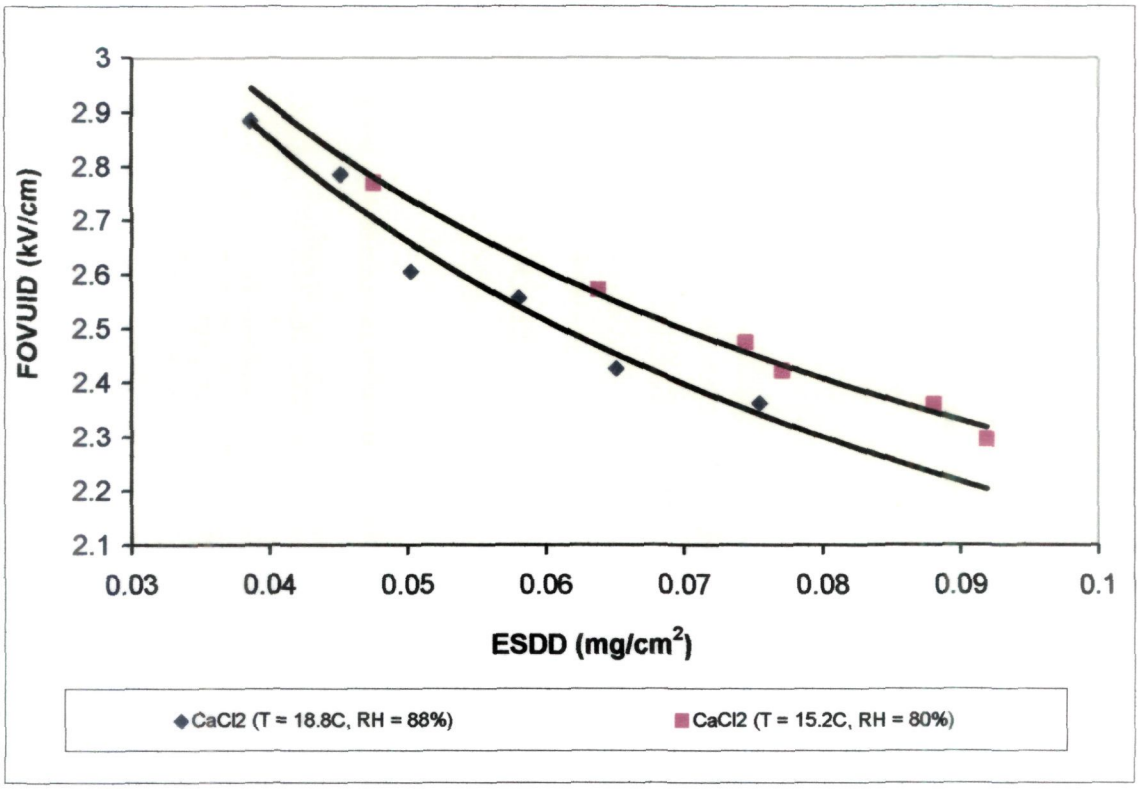


Fig. 4.75: FOVUID vs ESDD Curve for $CaCl_2$ at different temperature and relative humidity.

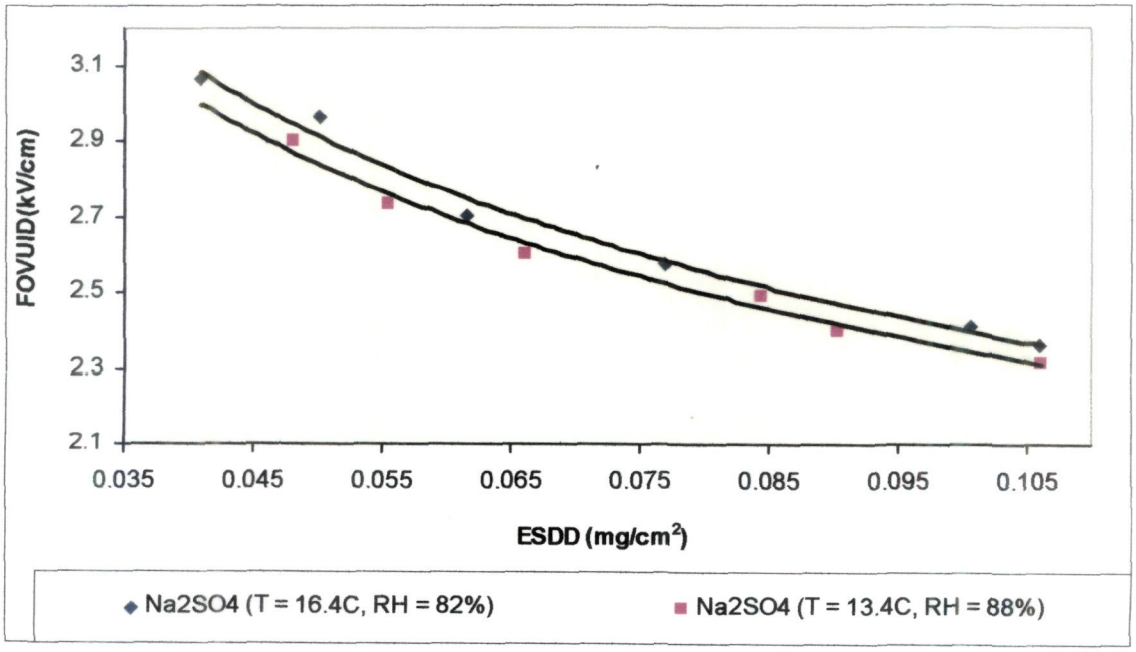


Fig. 4.76: FOVUID vs ESDD Curve for Na_2SO_4 at different temperature and relative humidity.

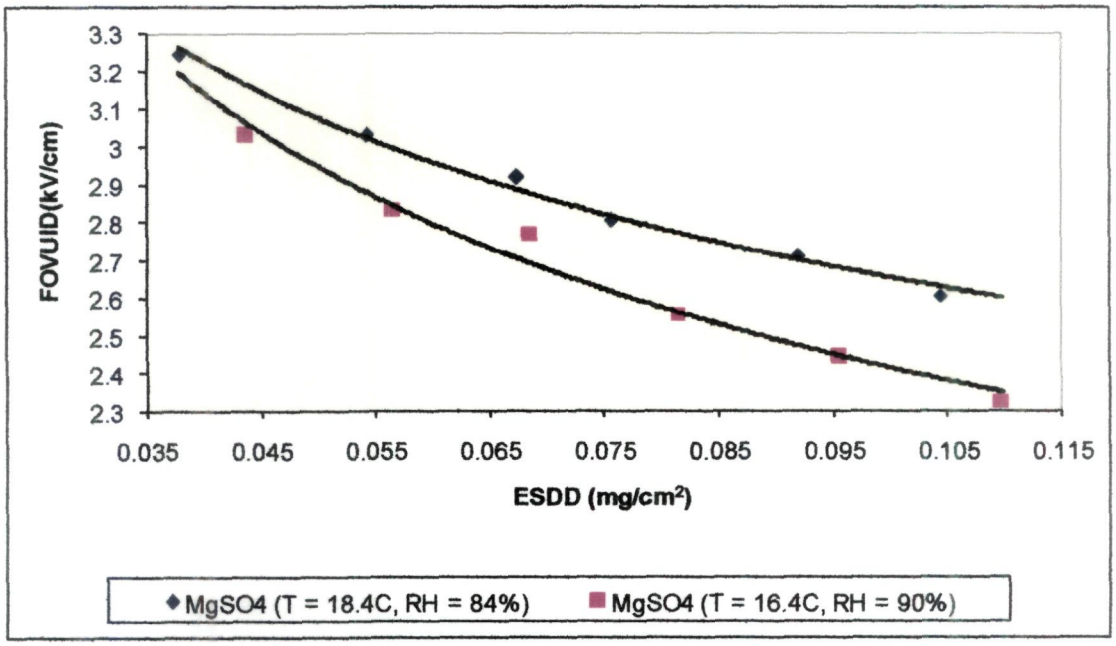


Fig. 4.77: FOVUID vs ESDD Curve for $MgSO_4$ at different temperature and relative humidity.

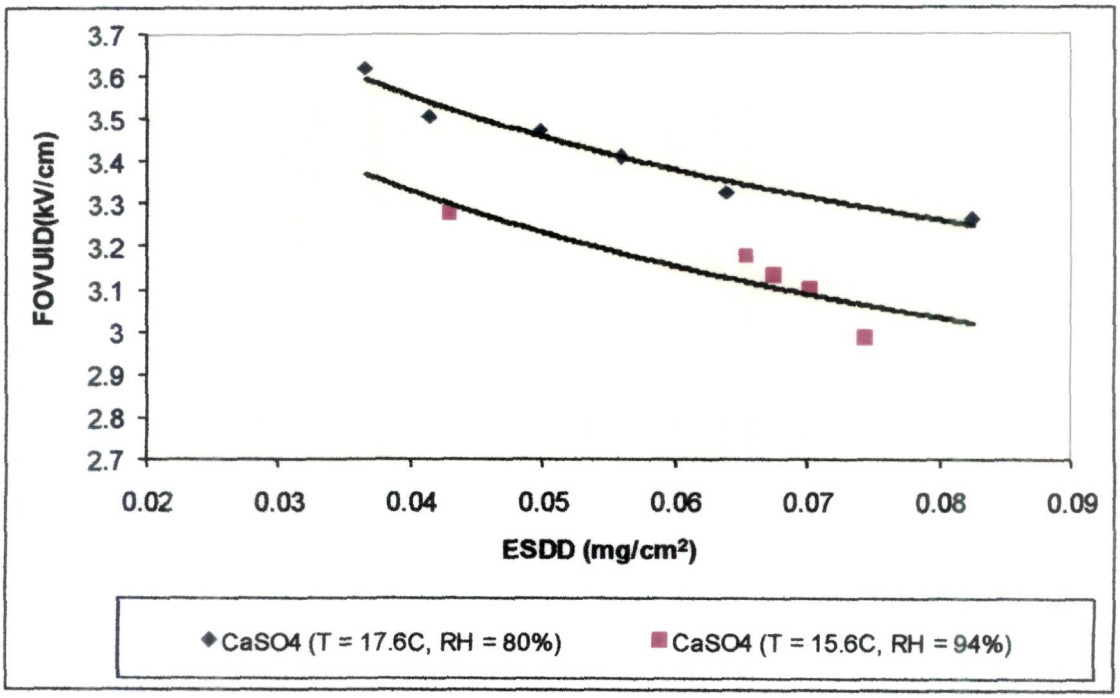


Fig. 4.78: FOVUID vs ESDD Curve for $CaSO_4$ at different temperature and relative humidity.

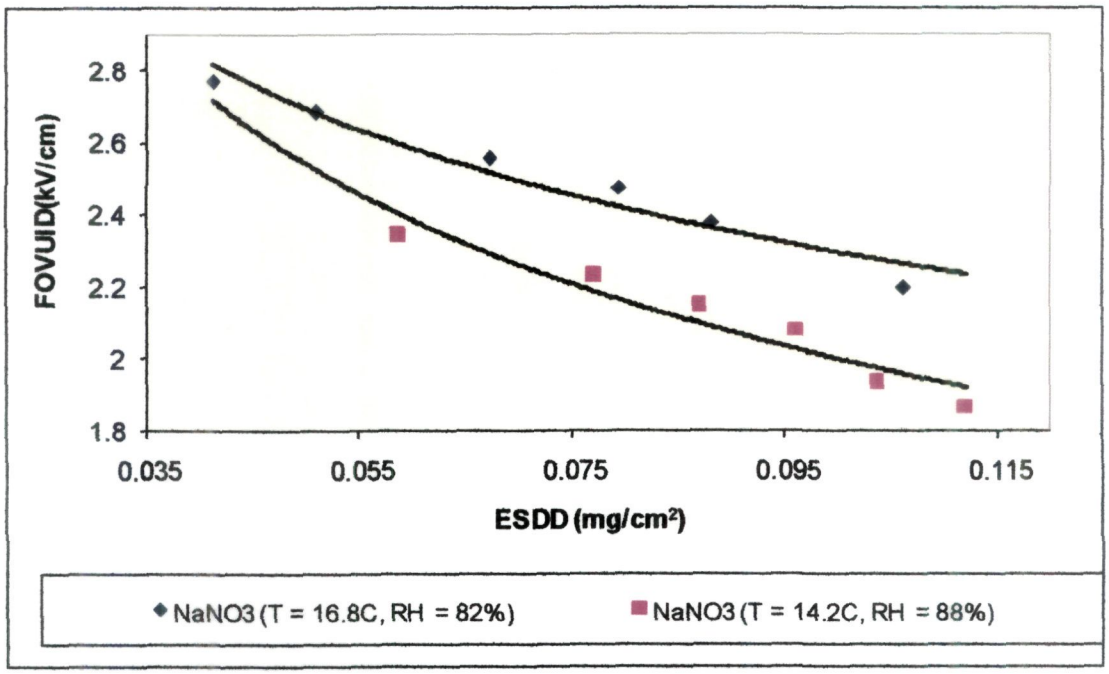


Fig. 4.79: FOVUID vs ESDD Curve for $NaNO_3$ at different temperature and relative humidity.

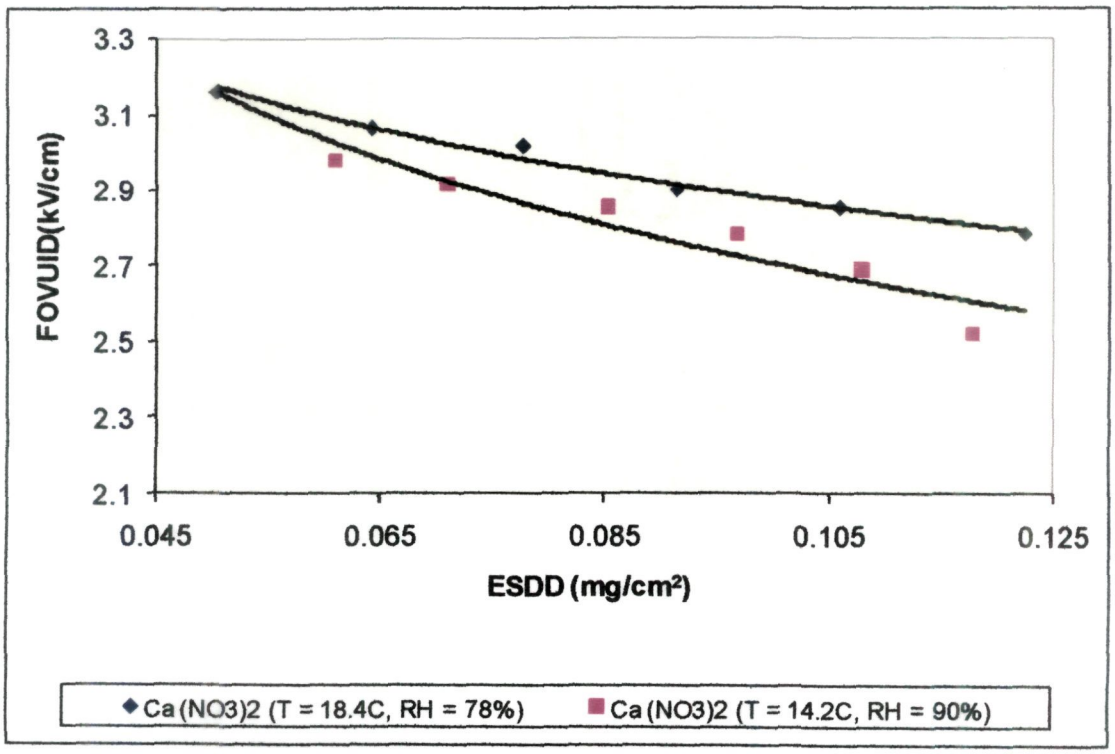


Fig. 4.80: FOVUID vs ESDD Curve for Ca $(NO_3)_2$ at different temperature and relative humidity.

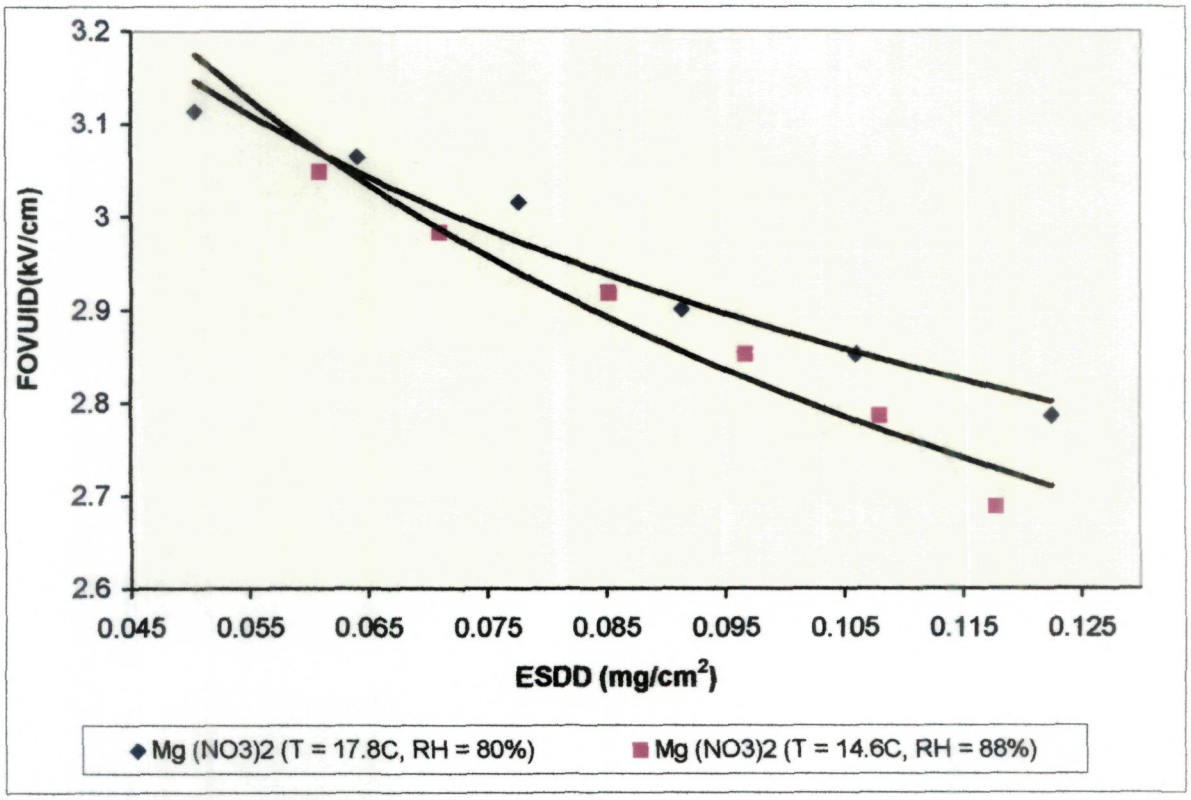


Fig. 4.81: FOVUID vs ESDD Curve for Mg $(NO_3)_2$ at different temperature and relative humidity.

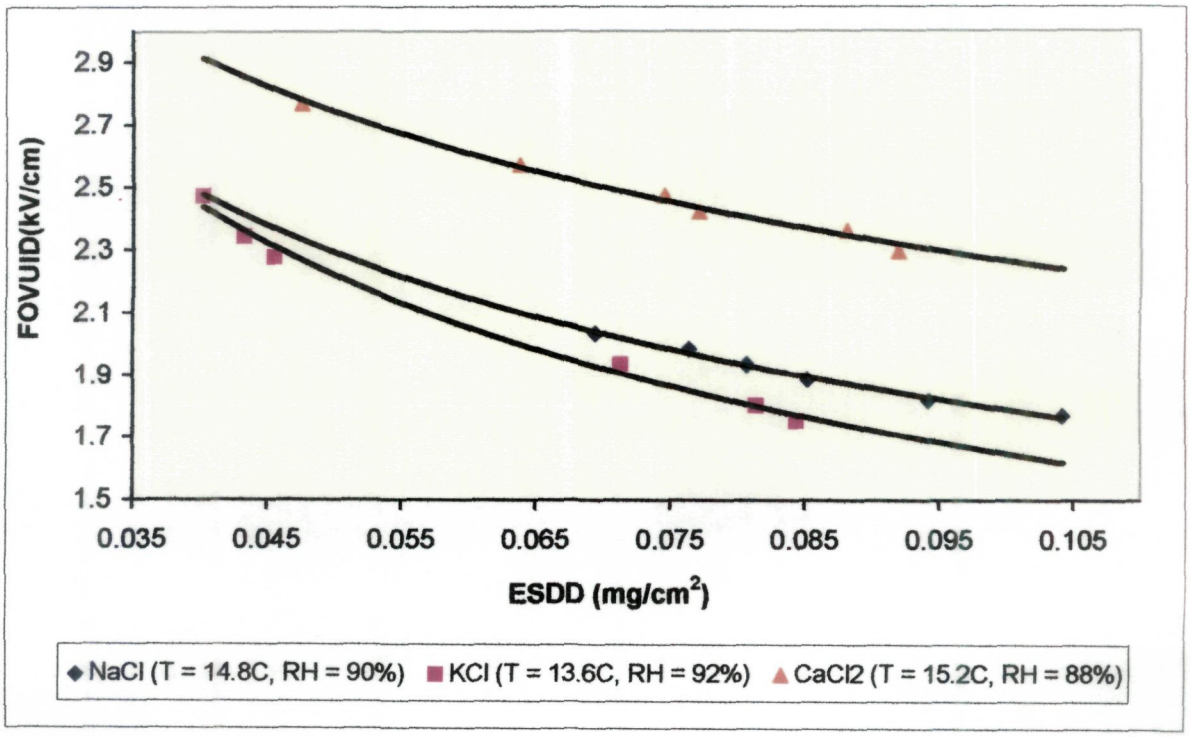


Fig. 4.82: FOVUID vs ESDD Curve for Chlorides.

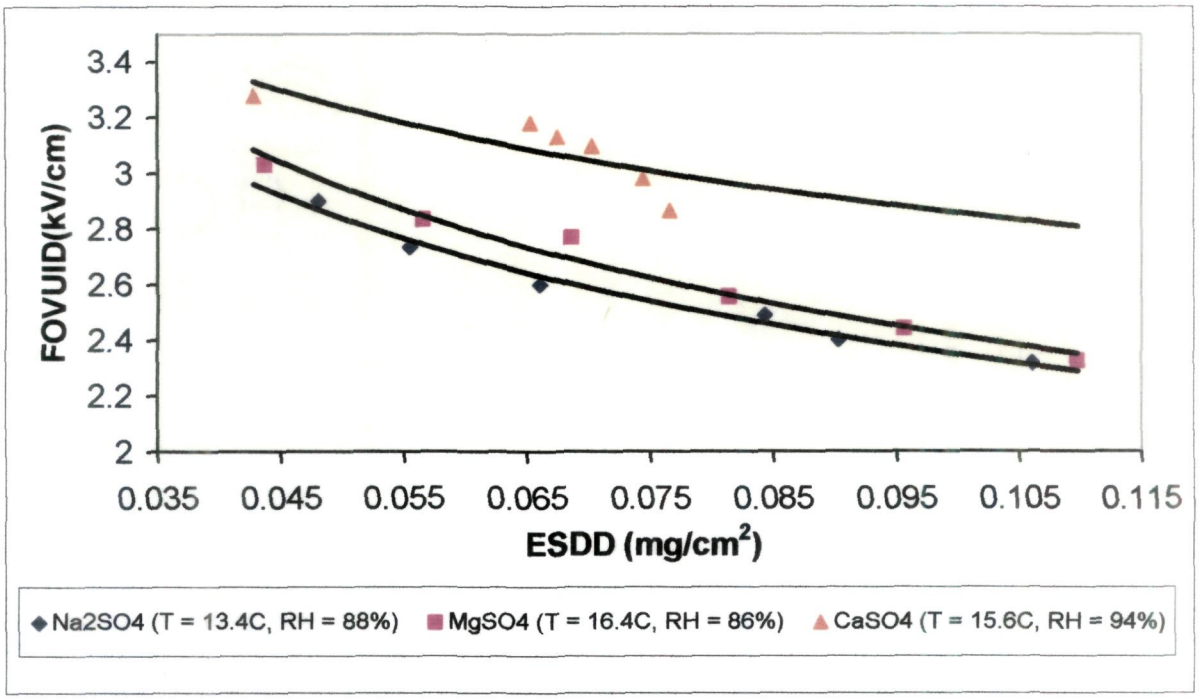


Fig. 4.83: FOVUID vs ESDD Curve for Sulphates.

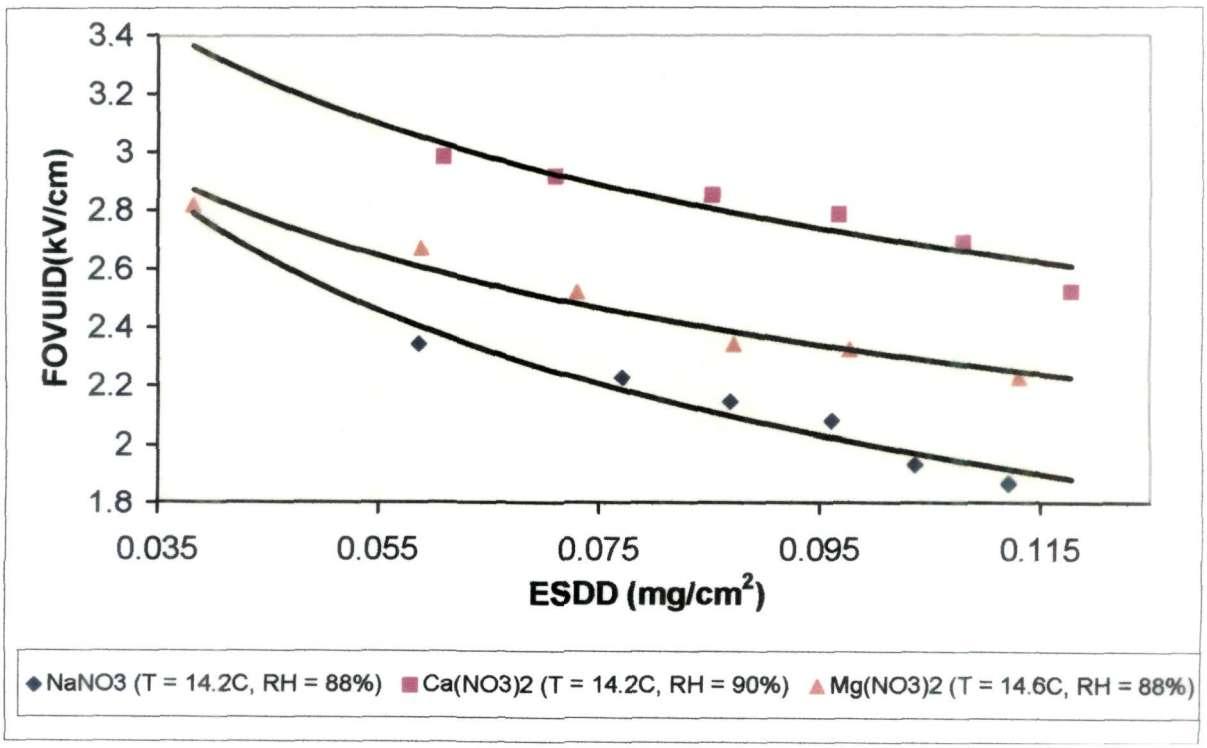


Fig. 4.84: FOVUID vs ESDD Curve for Nitrates.

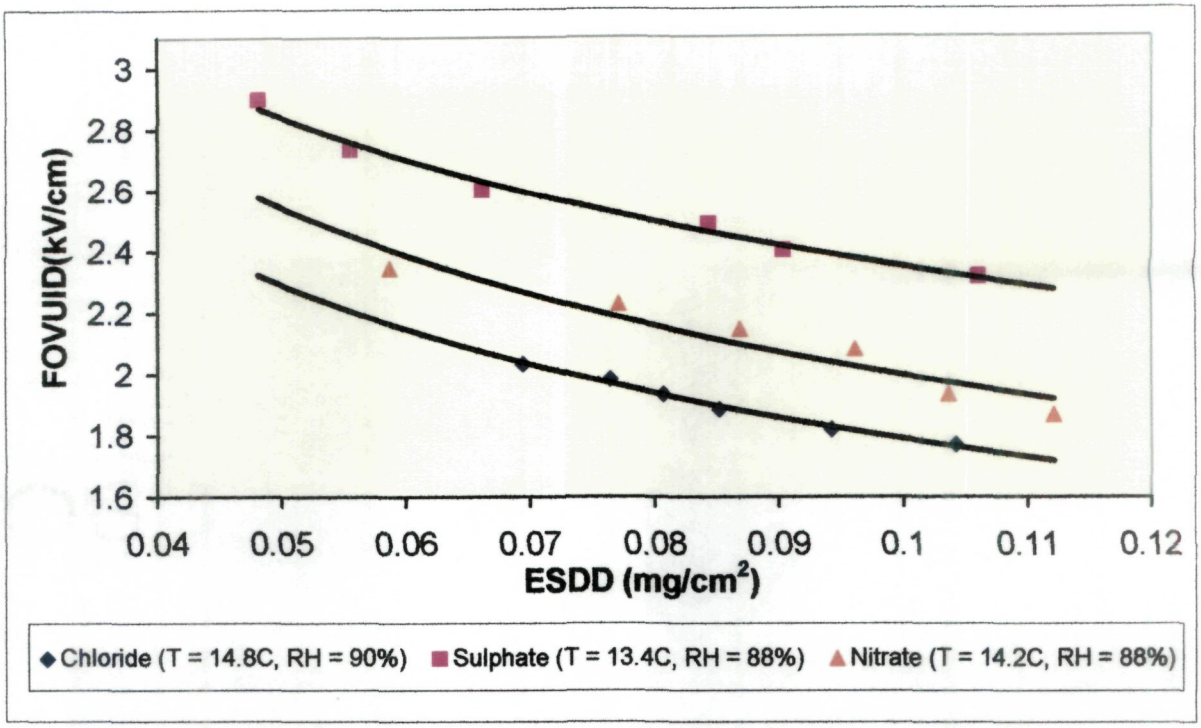


Fig. 4.85: FOVUID vs ESDD Curve for Na^+ Cation and different anions

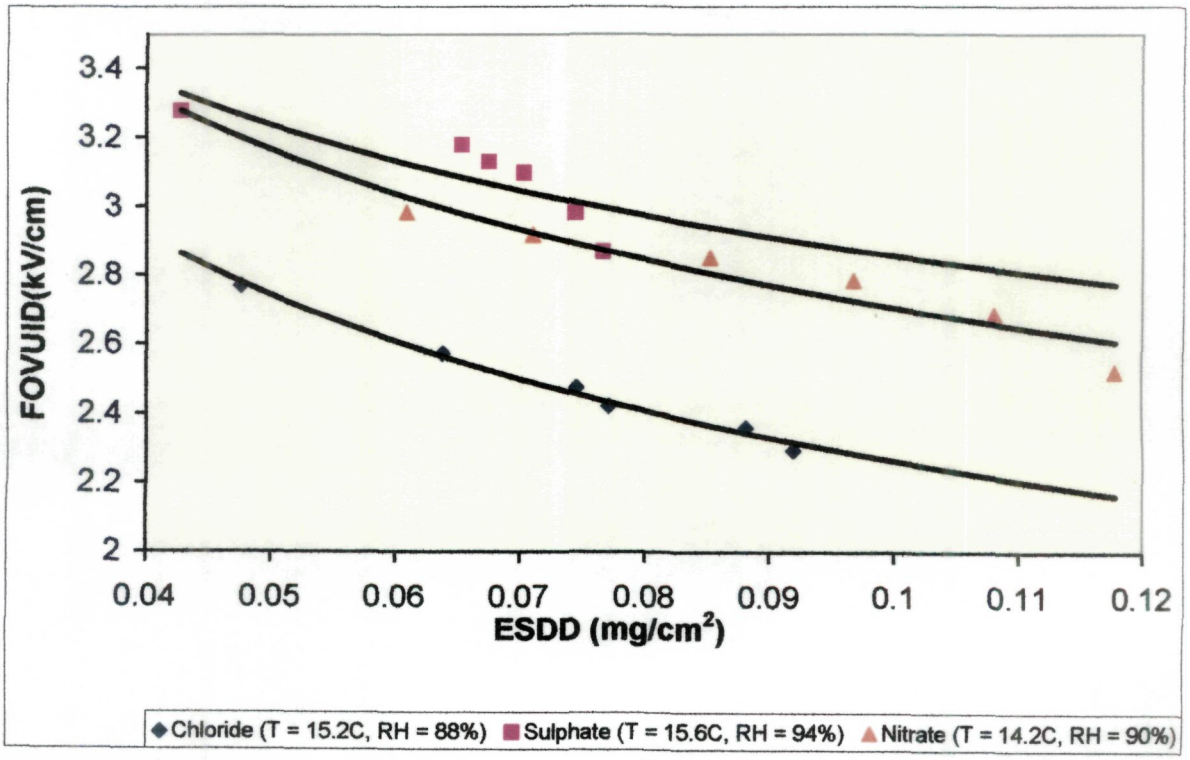


Fig. 4.86: FOVUID vs ESDD Curve for Ca^{2+} Cation and different anions

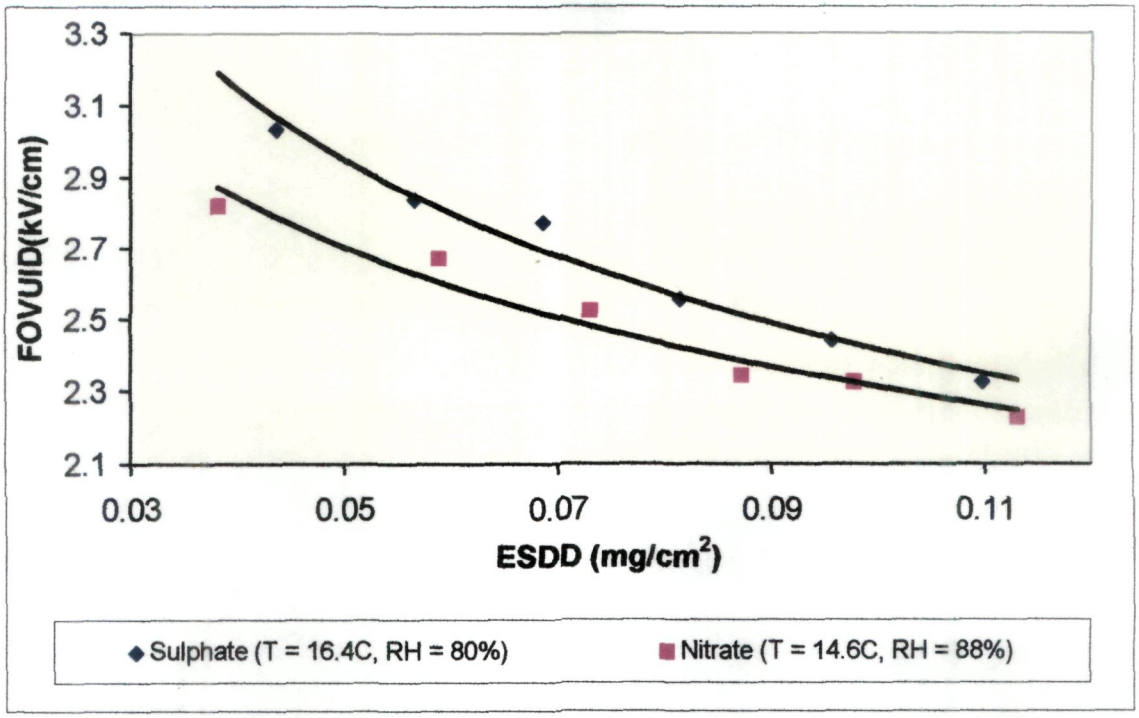


Fig. 4.87: FOVUID vs ESDD Curve for Mg^{2+} Cation and different anions

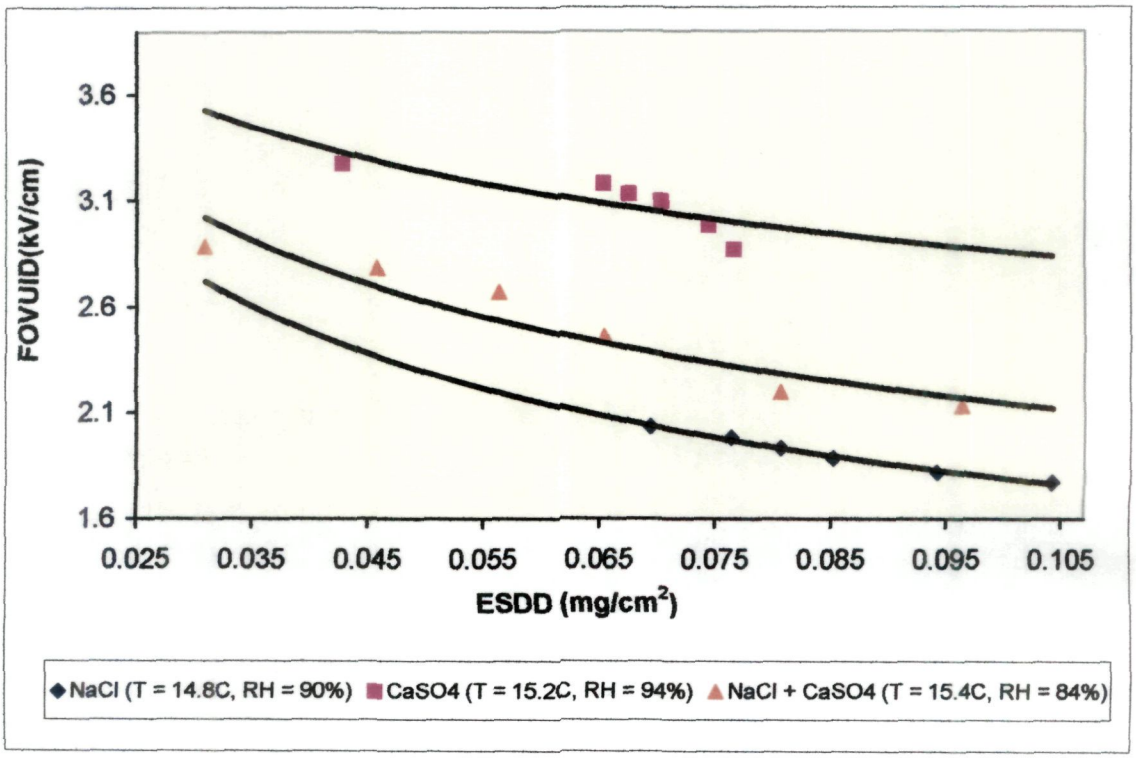


Fig. 4.88: FOVUID vs ESDD Curve for Single and Double Salts.

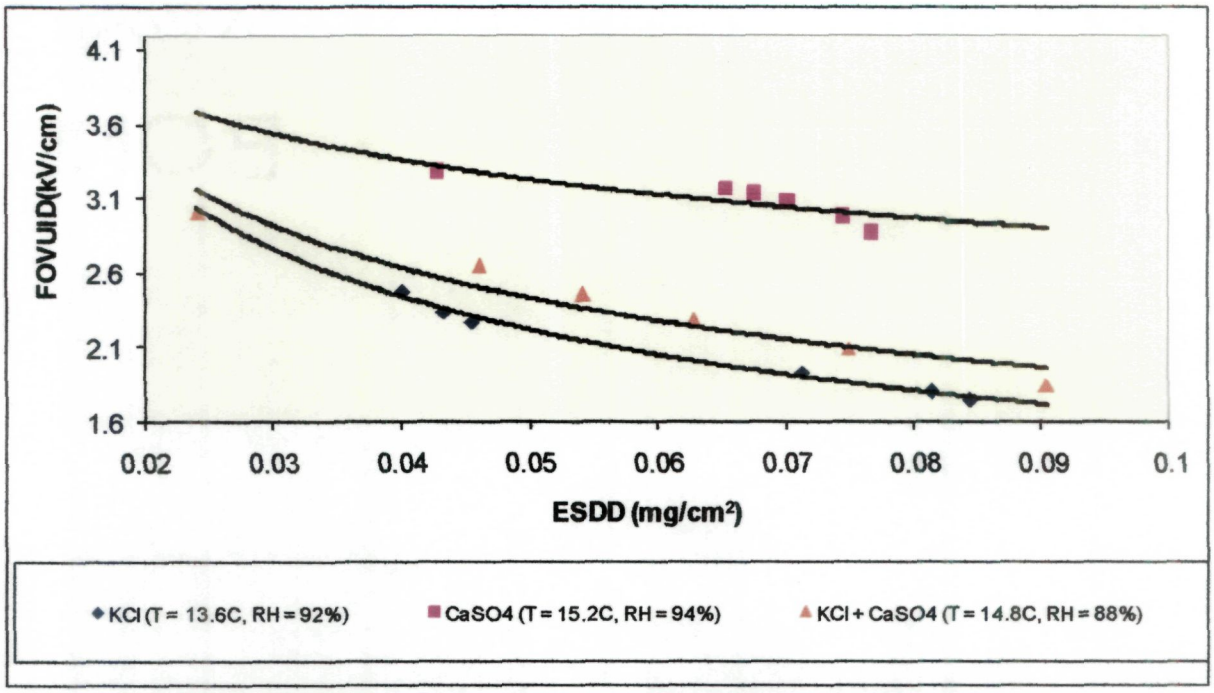


Fig. 4.89: FOVUID vs ESDD Curve for Single and Double Salts.

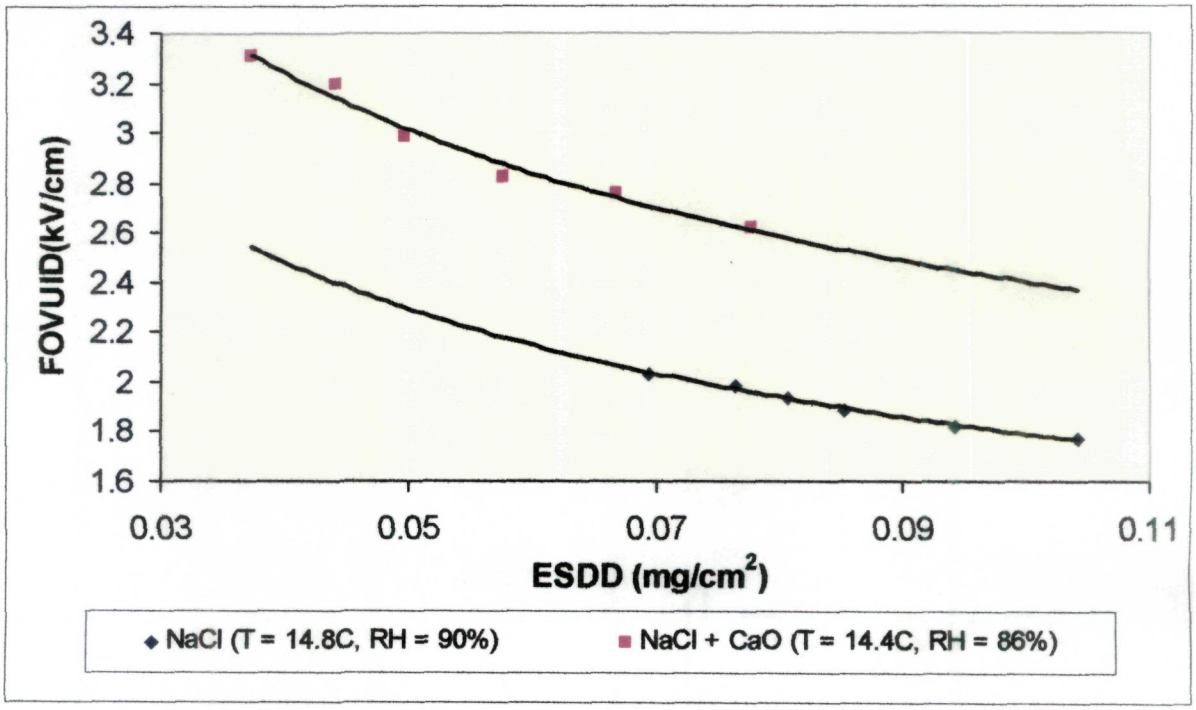


Fig. 4.90: FOVUID vs ESDD Curve for Single and Double Salts.

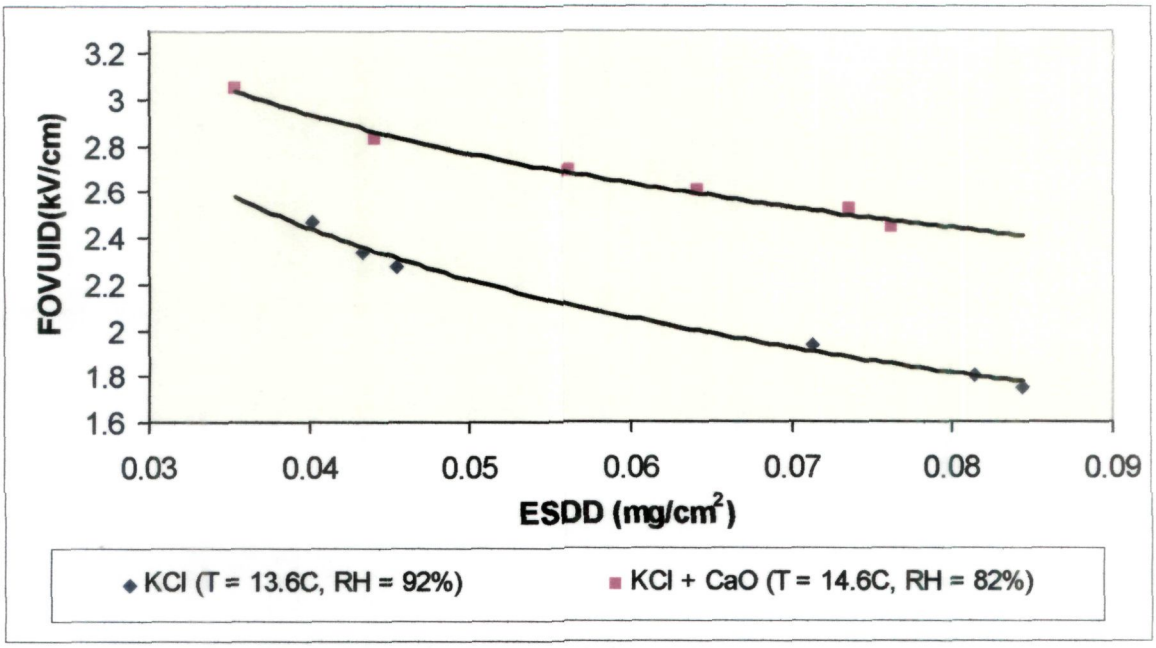


Fig. 4.91: FOVUID vs ESDD Curve for Single and Double Salts.

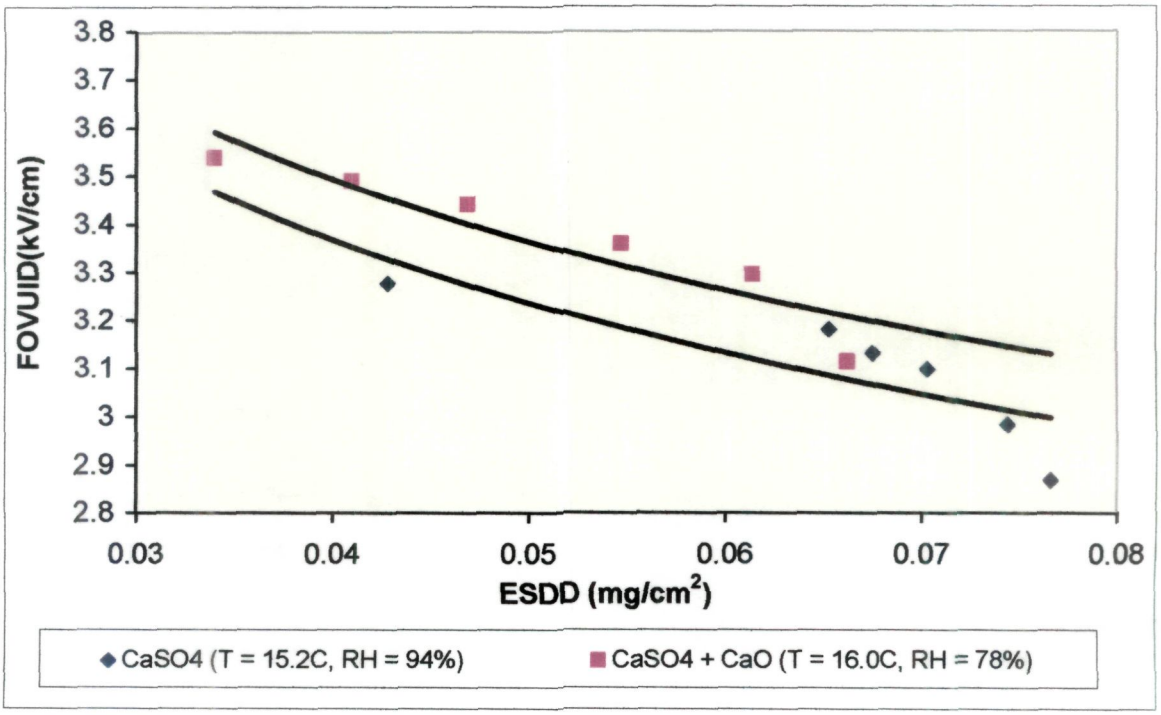


Fig. 4.92: FOVUID vs ESDD Curve for Single and Double Salts.

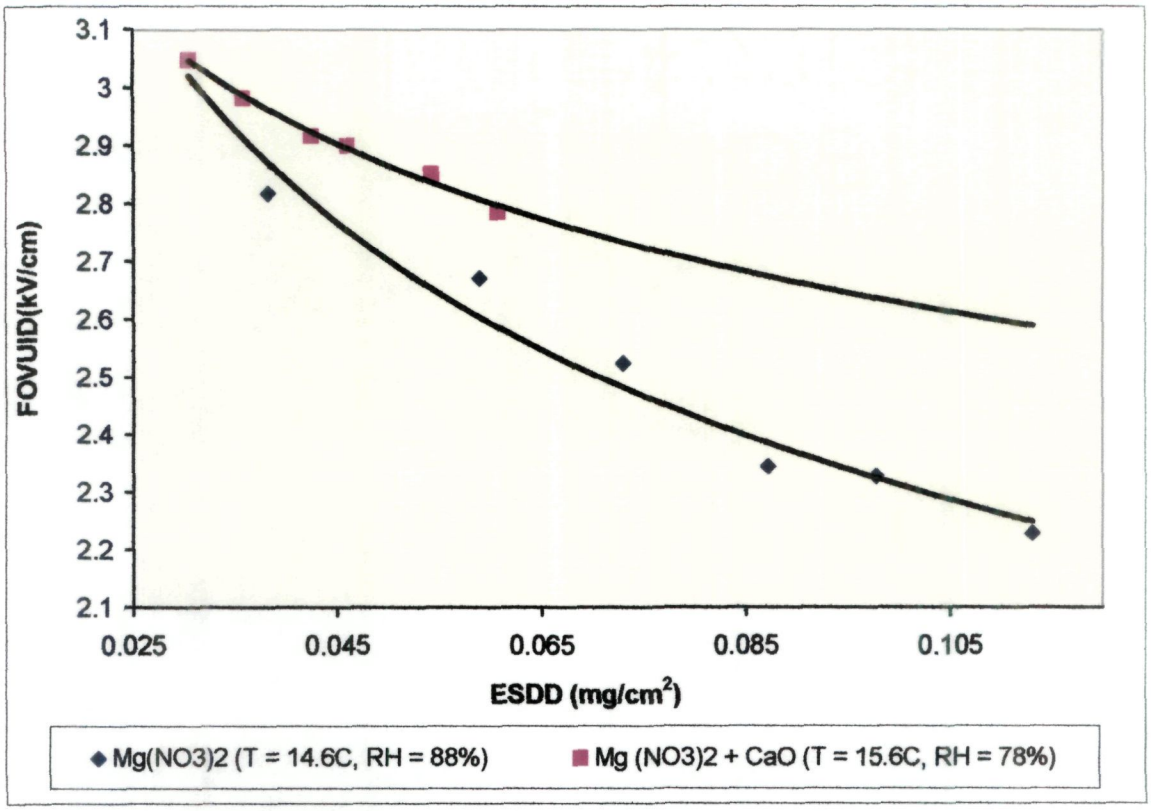


Fig. 4.93: FOVUID vs ESDD Curve for Single and Double Salts.

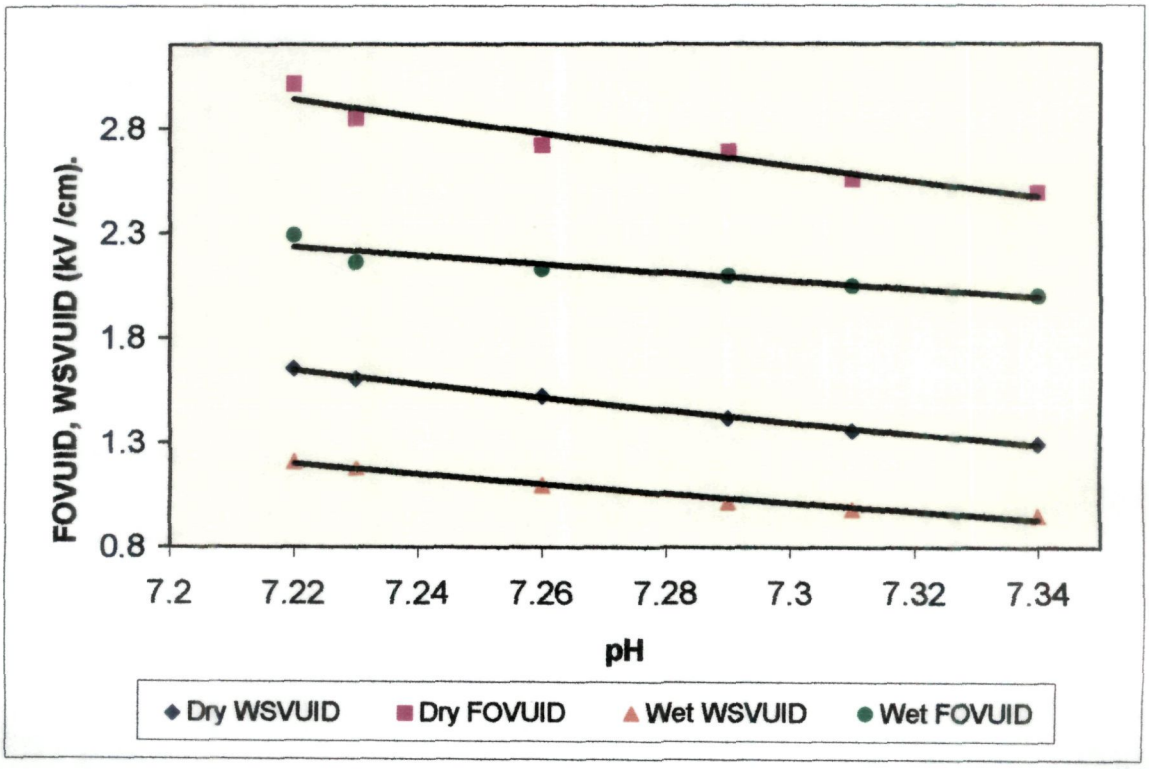


Fig. 4.94: FOVUID, WSVUID vs pH Curve for NaCl

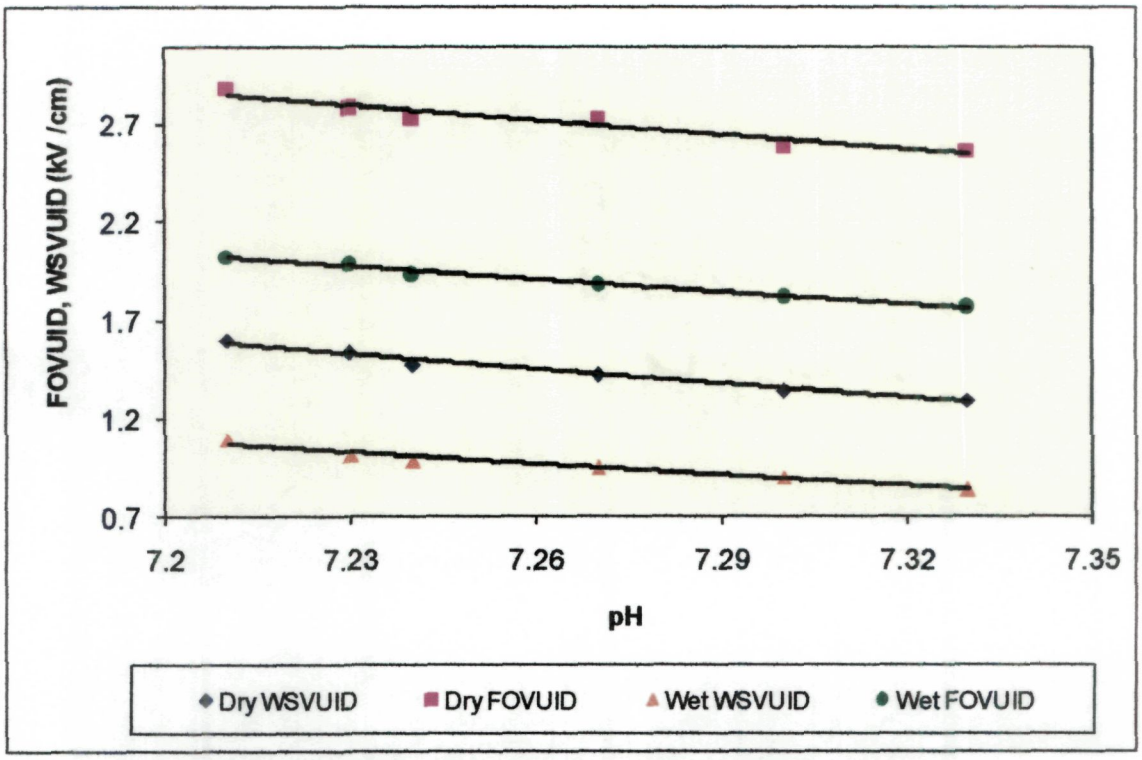


Fig. 4.95: FOVUID, WSVUID vs pH Curve for NaCl

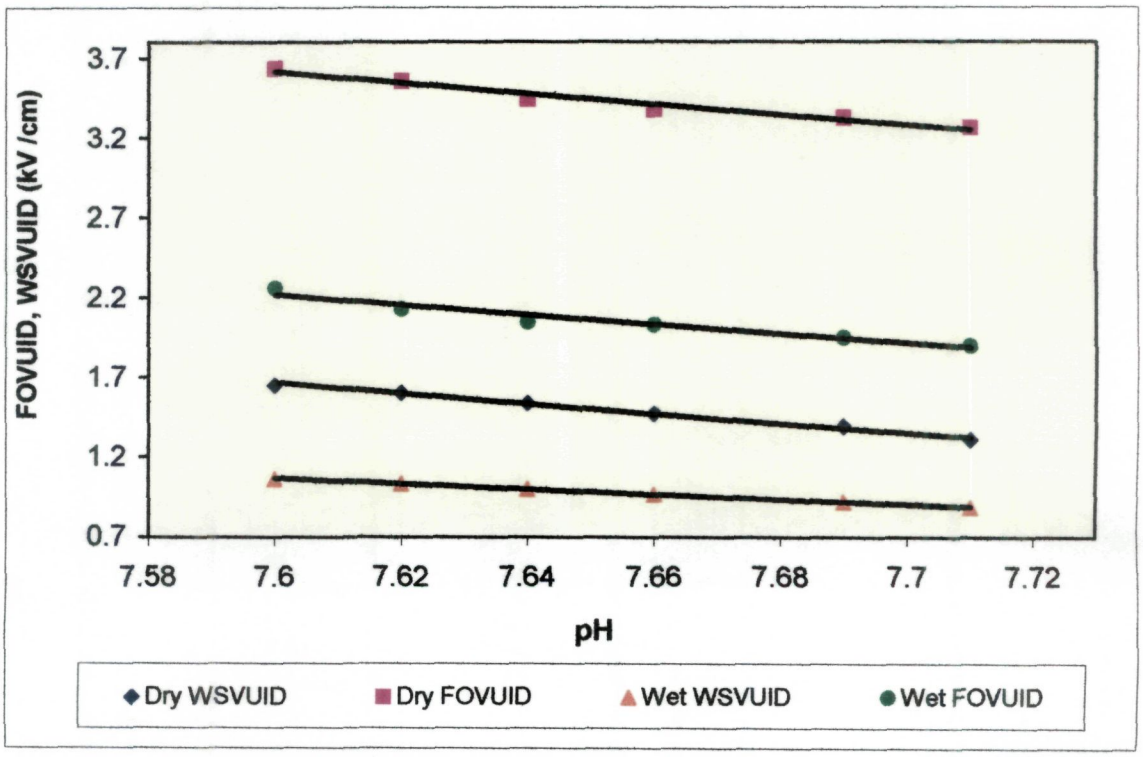


Fig. 4.96: FOVUID, WSVUID vs pH Curve for KCl

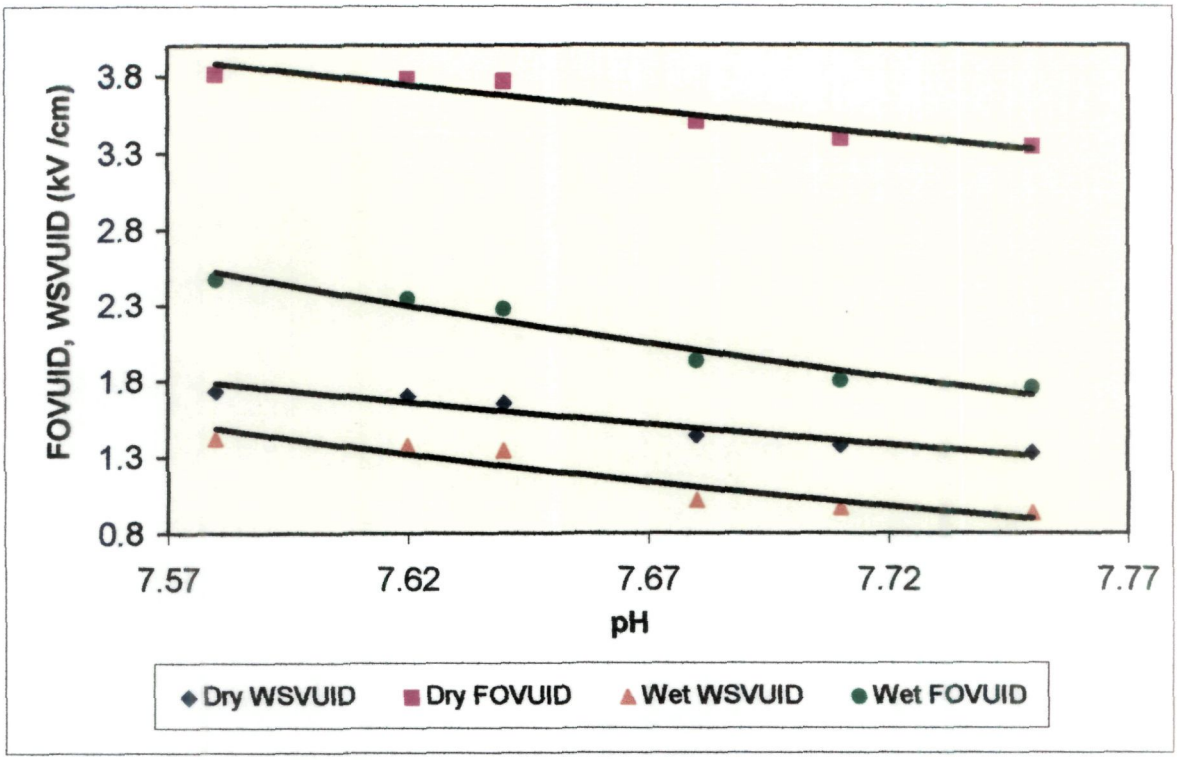


Fig. 4.97: FOVUID, WSVUID vs PH Curve for KCl

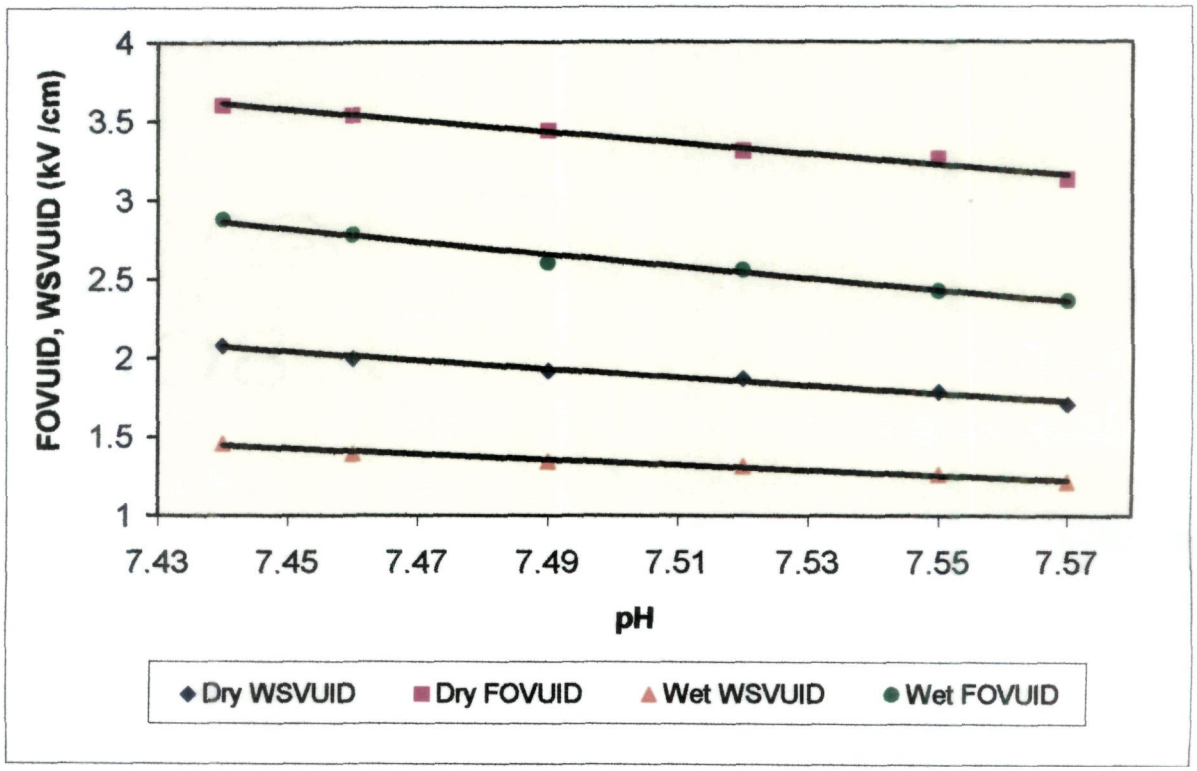


Fig. 4.98: FOVUID, WSVUID vs pH Curve for $CaCl_2$

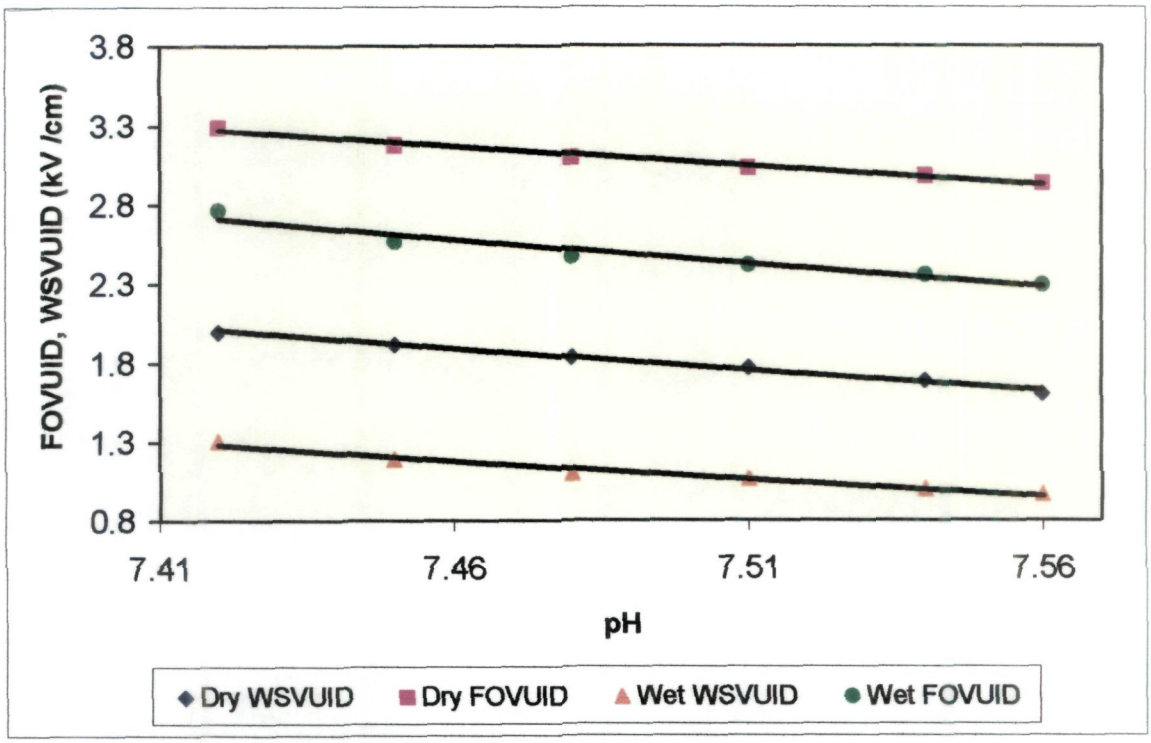


Fig. 4.99: FOVUID, WSVUID vs pH Curve for $CaCl_2$

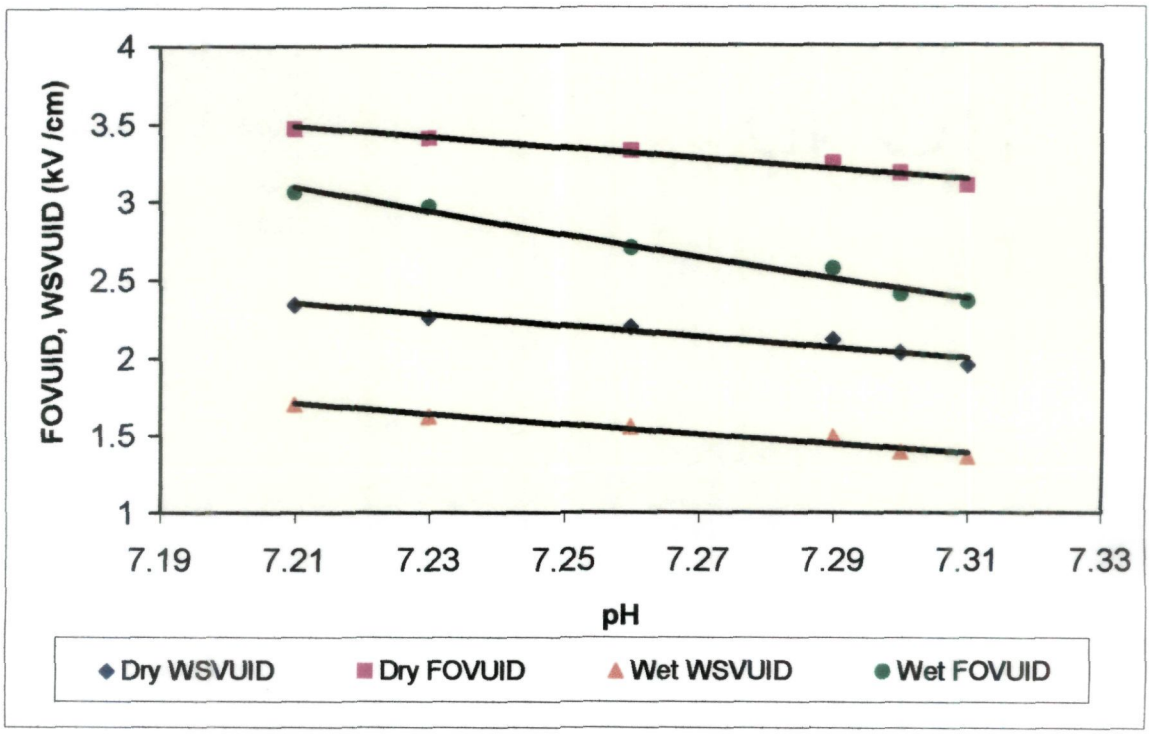


Fig. 4.100: FOVUID, WSVUID vs pH Curve for Na_2SO_4

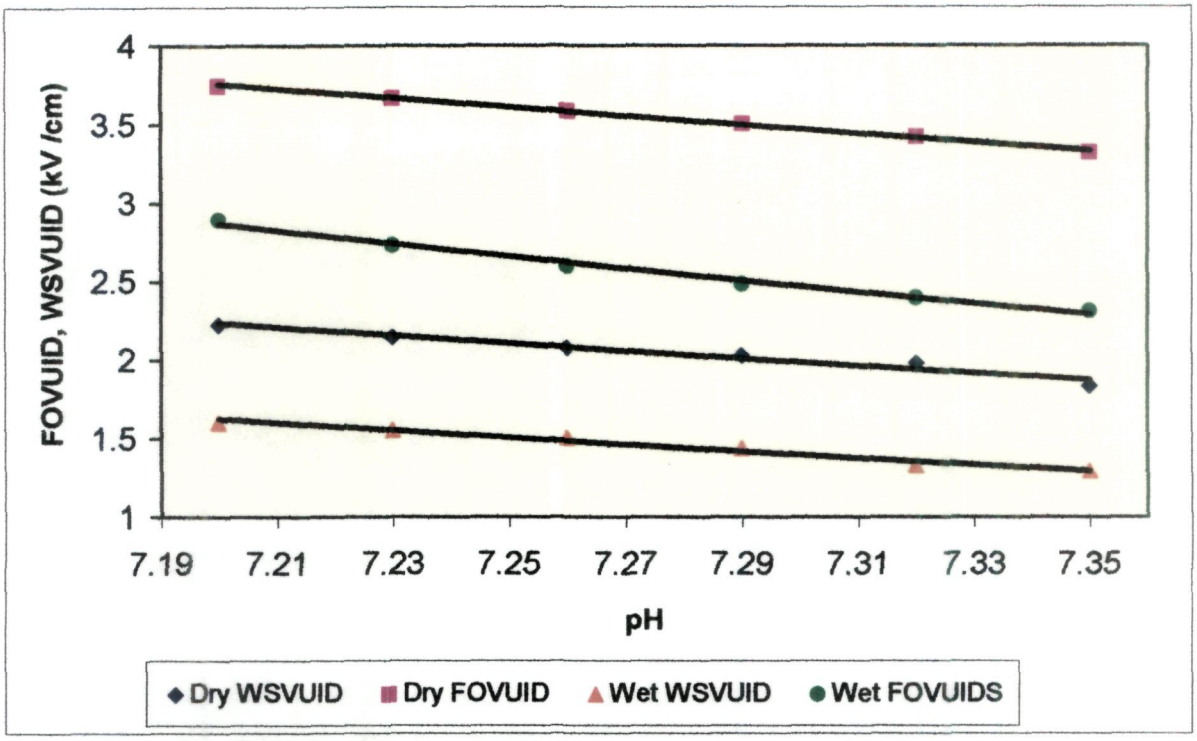


Fig. 4.101: FOVUID, WSVUID vs pH Curve for Na_2SO_4

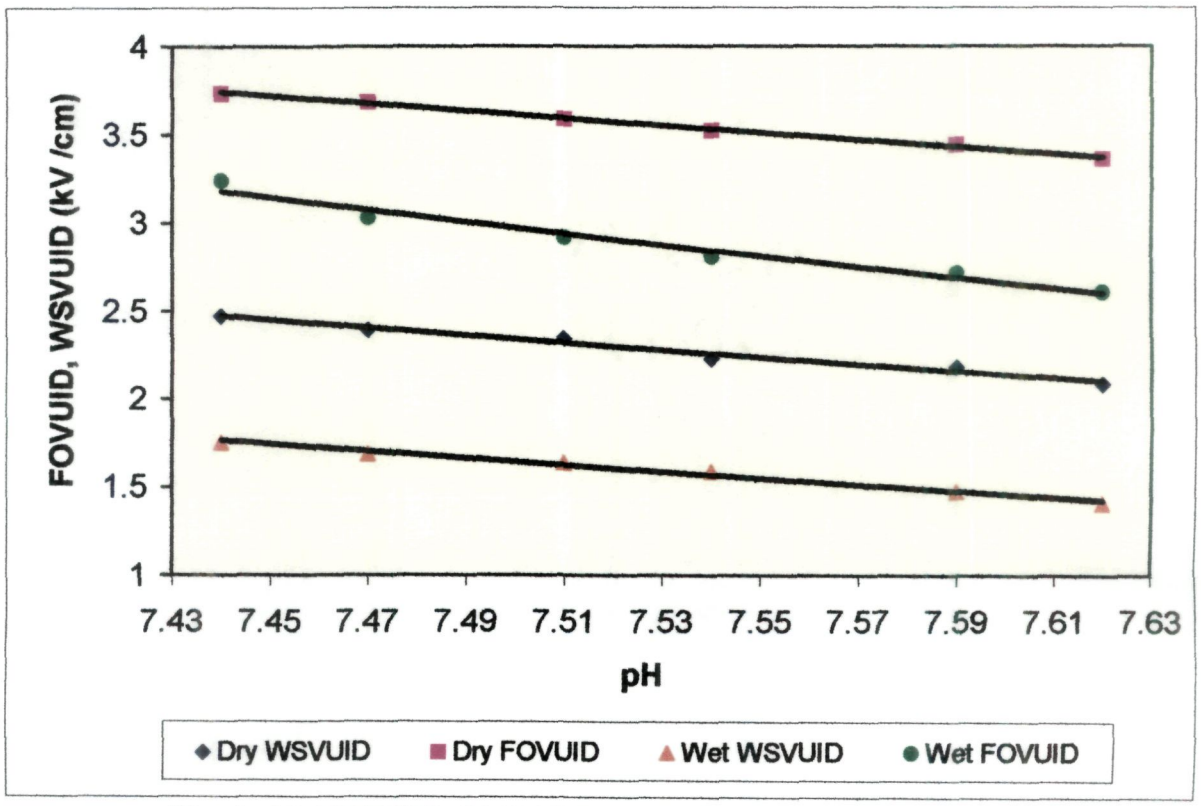


Fig. 4.102: FOVUID, WSVUID vs pH Curve for $MgSO_4$

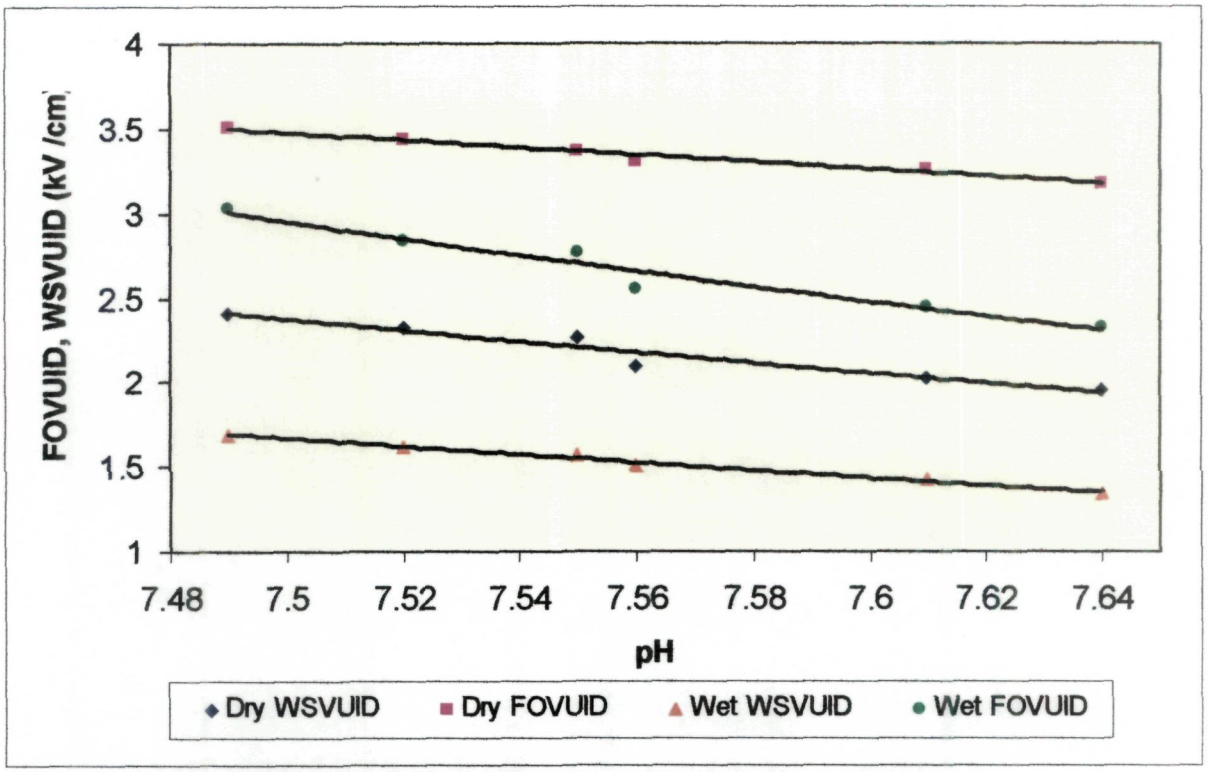


Fig. 4.103: FOVUID, WSVUID vs pH Curve for $MgSO_4$

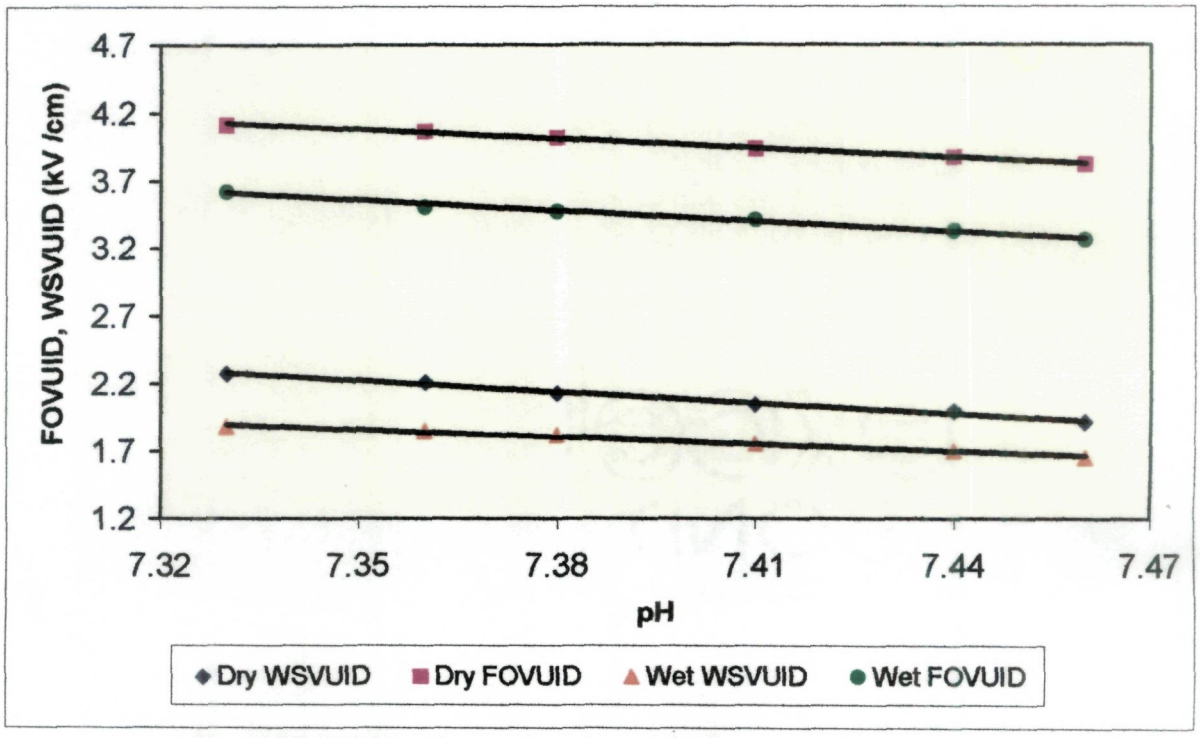


Fig. 4.104: FOVUID, WSVUID vs pH Curve for $CaSO_4$

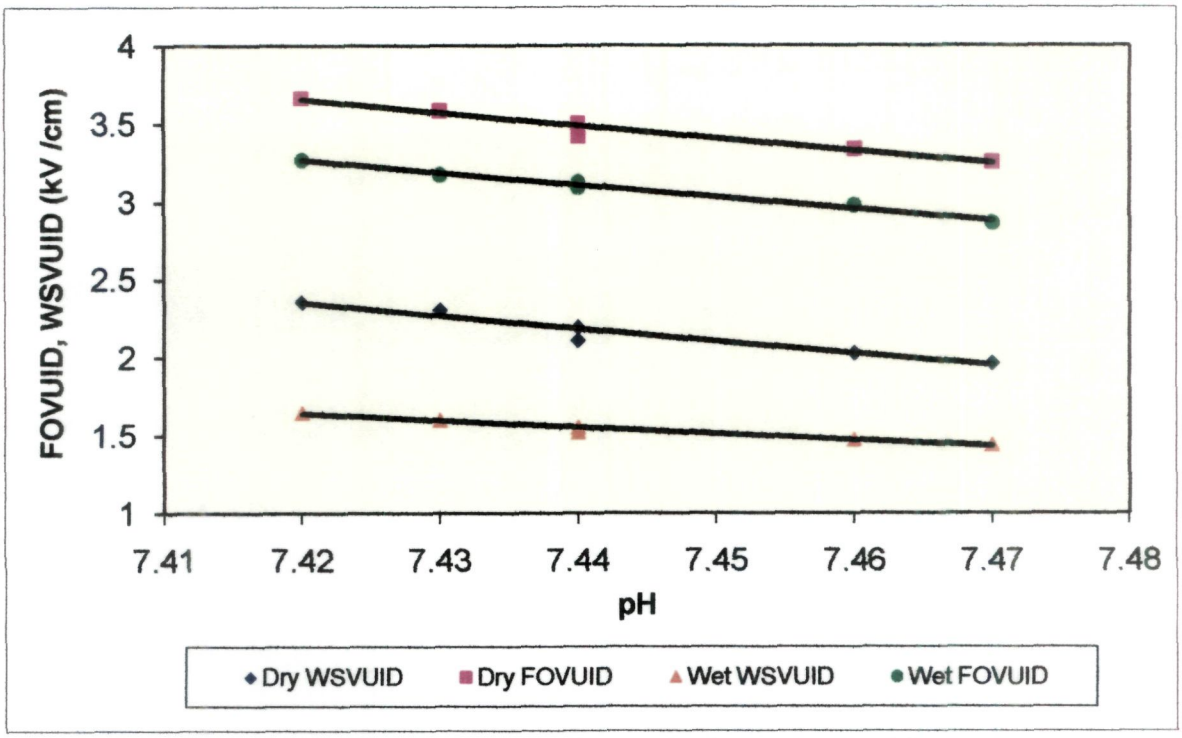


Fig. 4.105: FOVUID, WSVUID vs pH Curve for $CaSO_4$

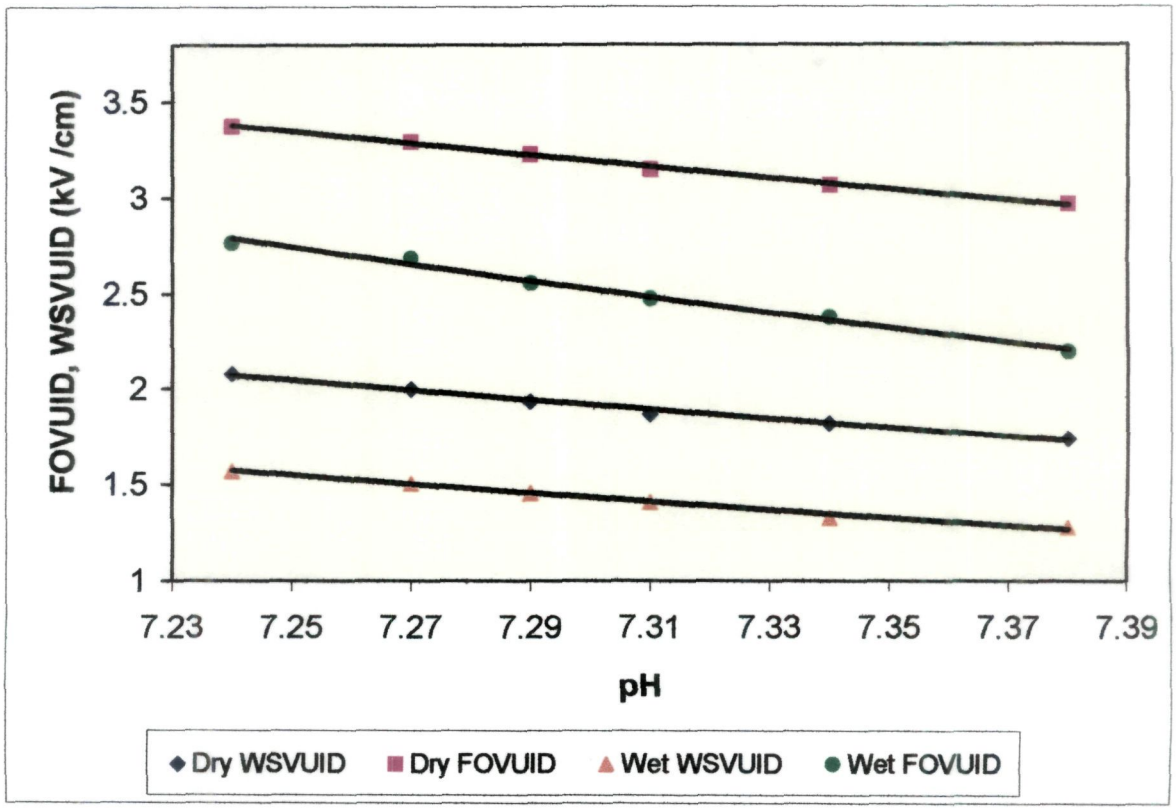


Fig. 4.106: FOVUID, WSVUID vs pH Curve for $NaNO_3$

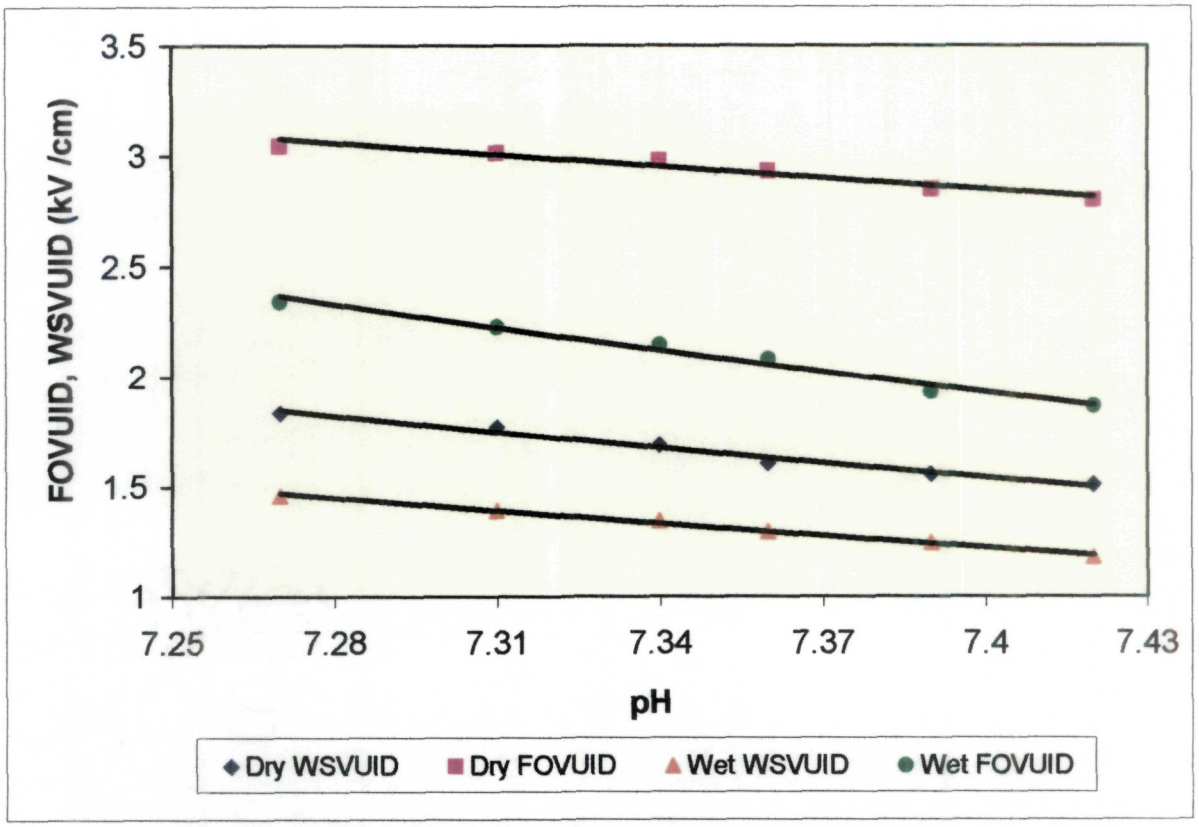


Fig. 4.107: FOVUID, WSVUID vs pH Curve for $NaNO_3$

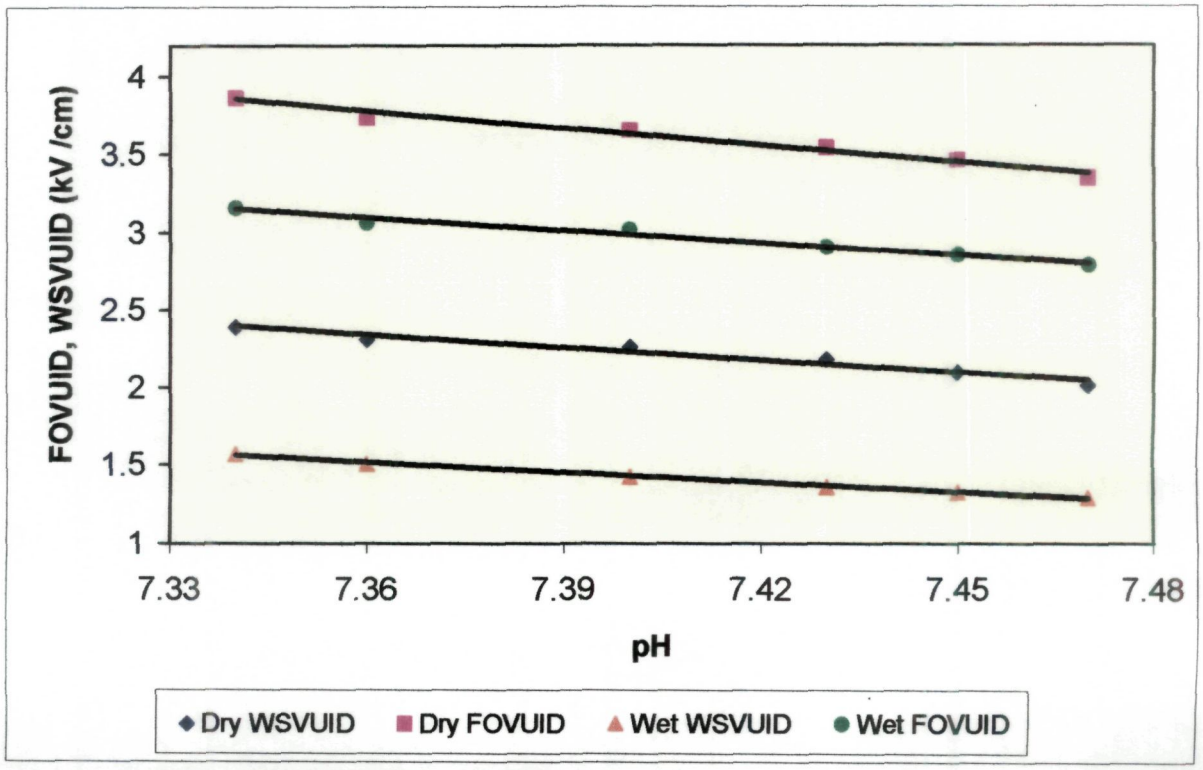


Fig. 4.108: FOVUID, WSVUID vs pH Curve for Ca $(NO_3)_2$

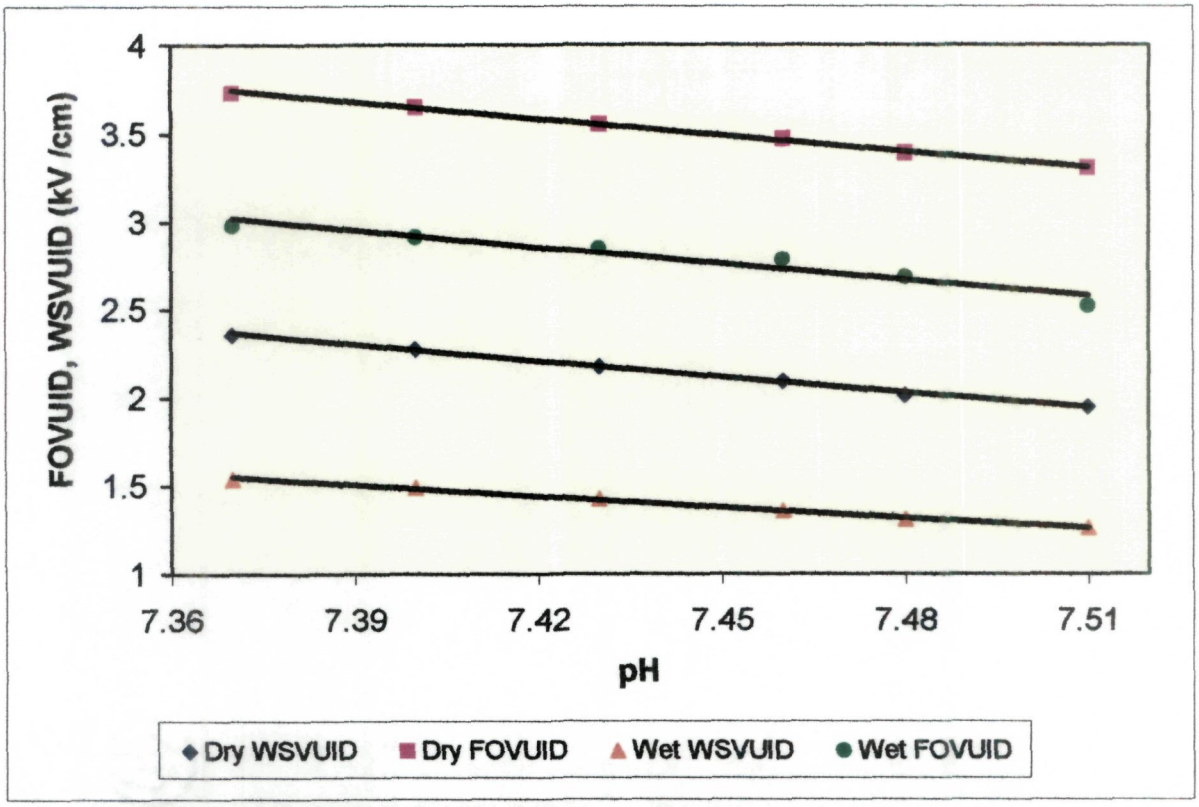


Fig. 4.109: FOVUID, WSVUID vs pH Curve for Ca $(NO_3)_2$

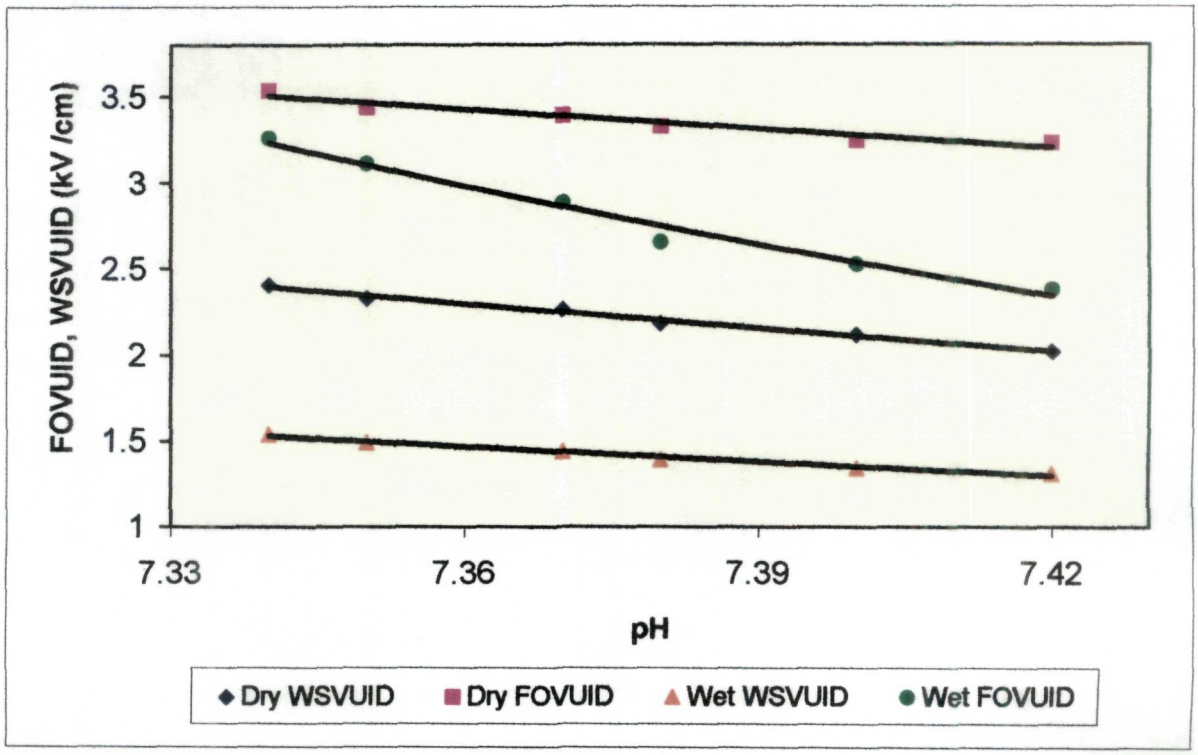


Fig. 4.110: FOVUID, WSVUID vs pH Curve for Mg $(NO_3)_2$

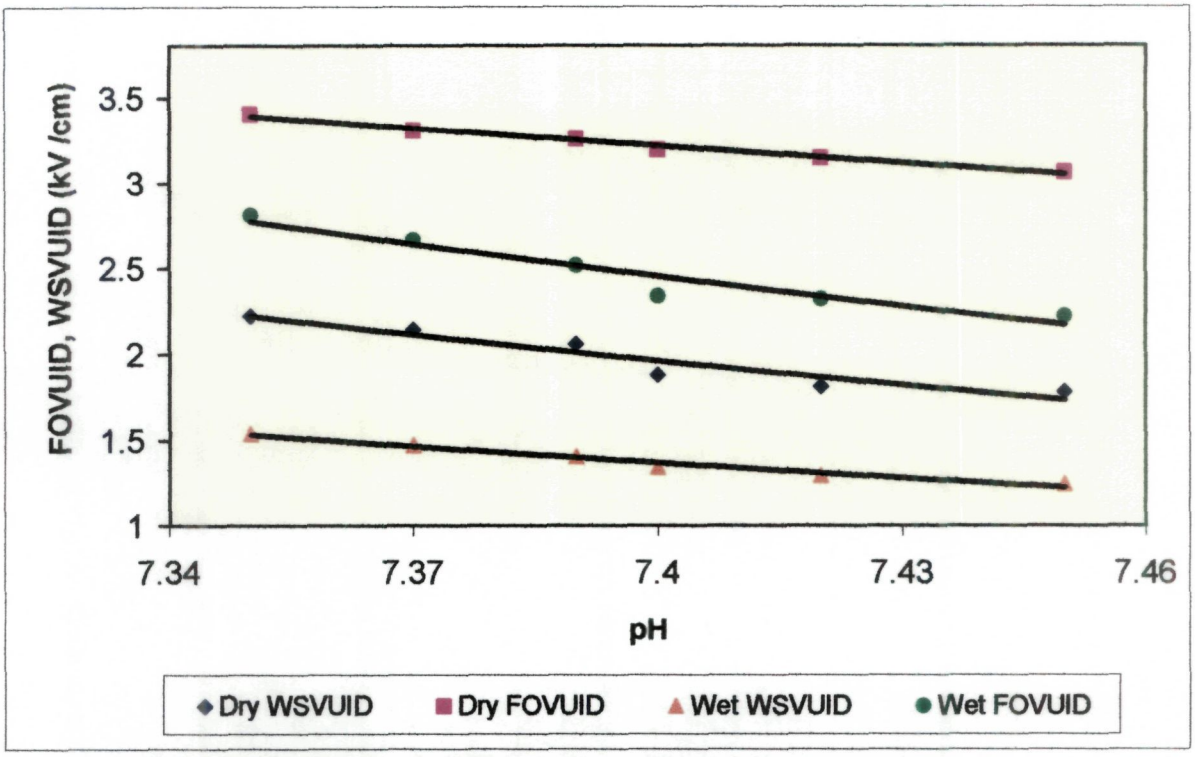


Fig. 4.111: FOVUID, WSVUID vs pH Curve for Mg $(NO_3)_2$

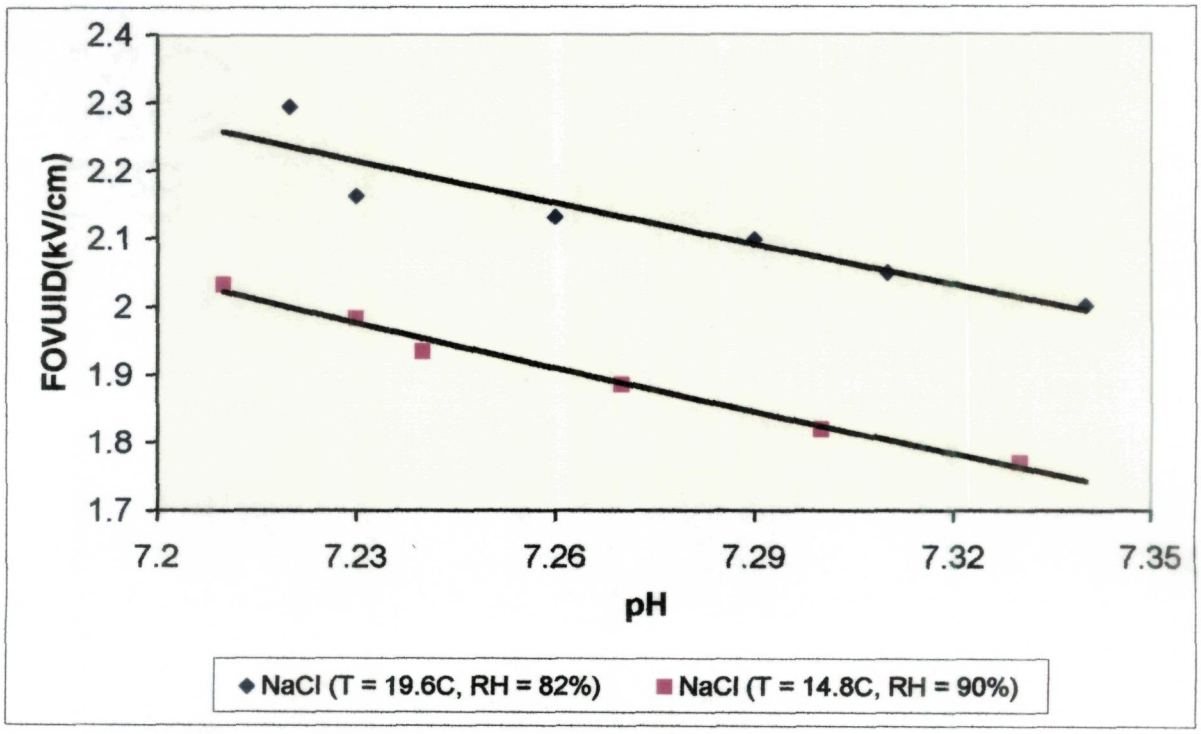


Fig. 4.112: FOVUID vs pH Curve for NaCl at different temperature and relative humidity.

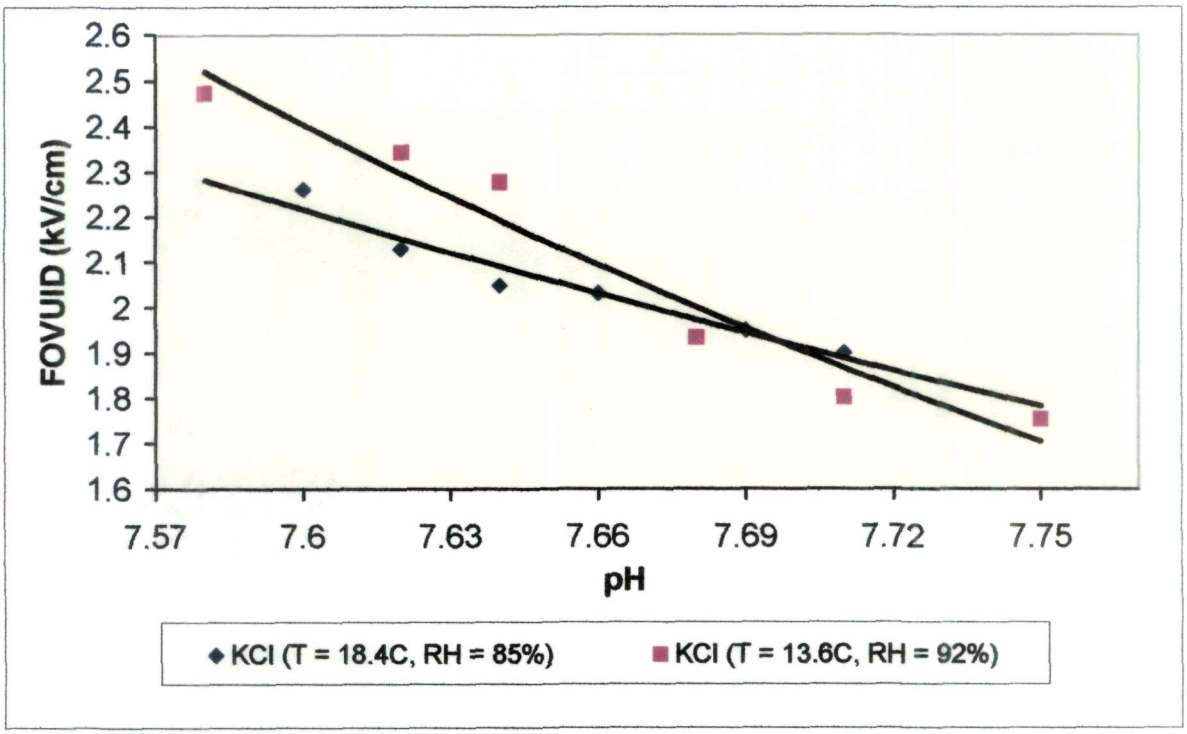


Fig. 4.113: FOVUID vs pH Curve for KCl at different temperature and relative humidity.

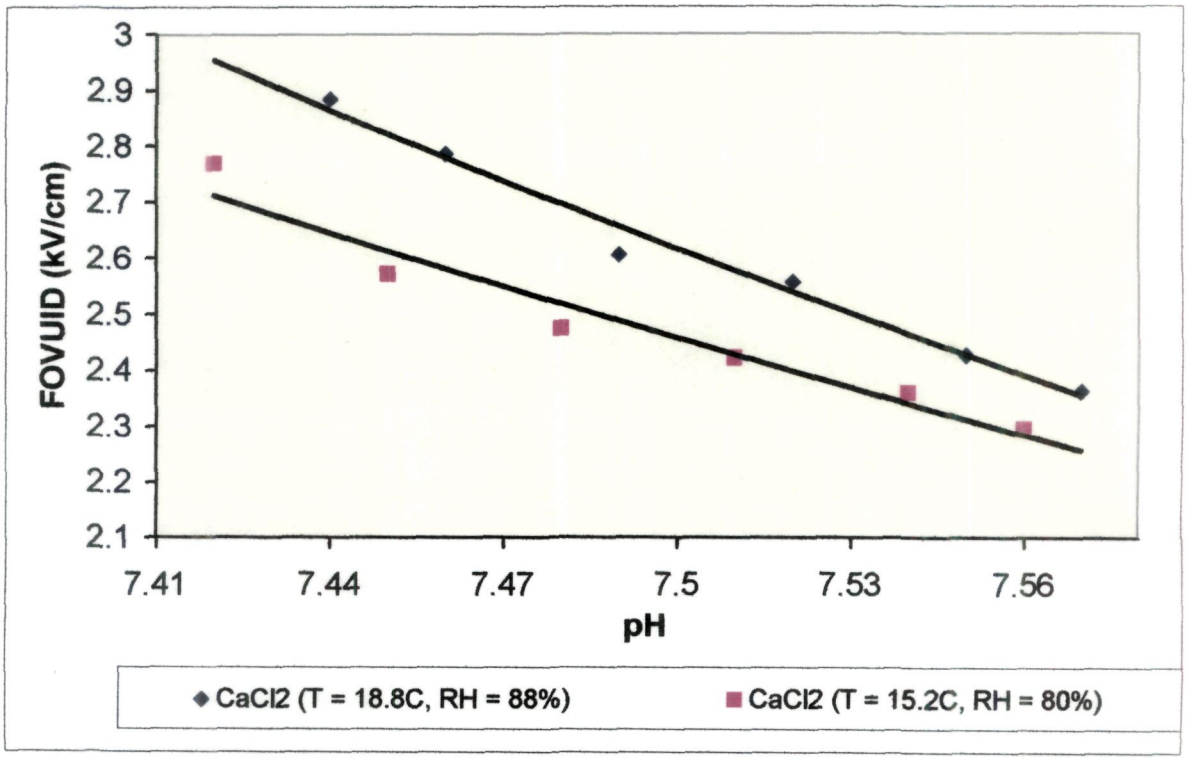


Fig. 4.114: FOVUID vs pH Curve for $CaCl_2$ at different temperature and relative humidity.

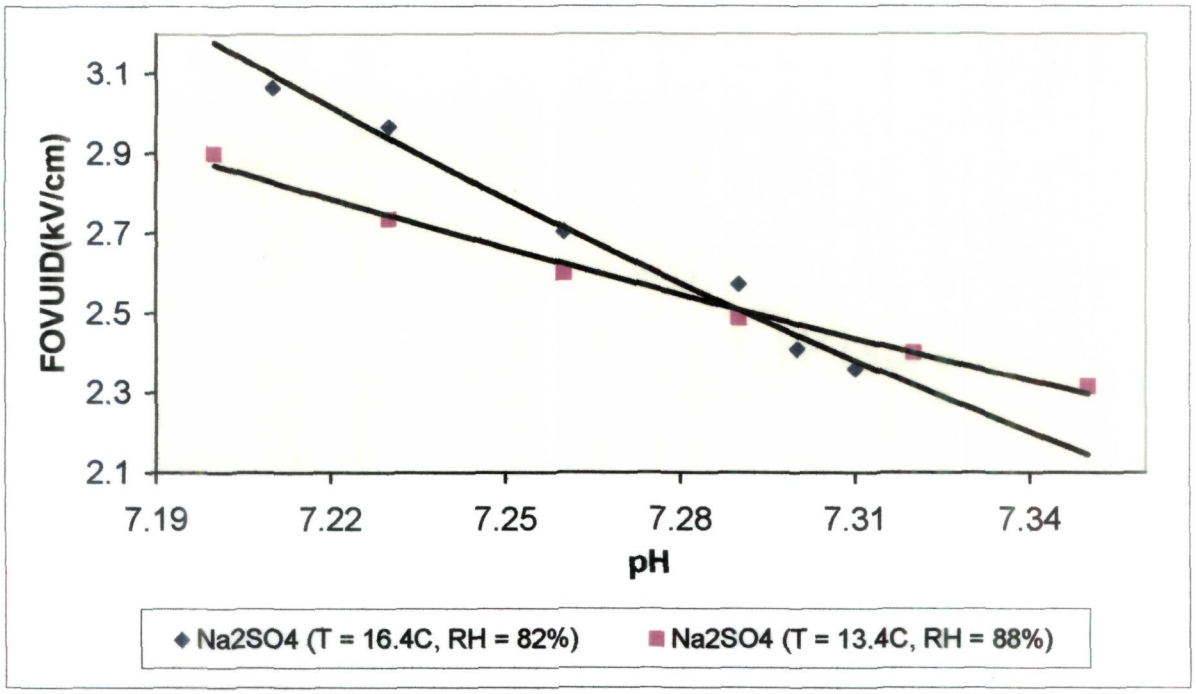


Fig. 4.115: FOVUID vs pH Curve for Na_2SO_4 at different temperature and relative humidity.

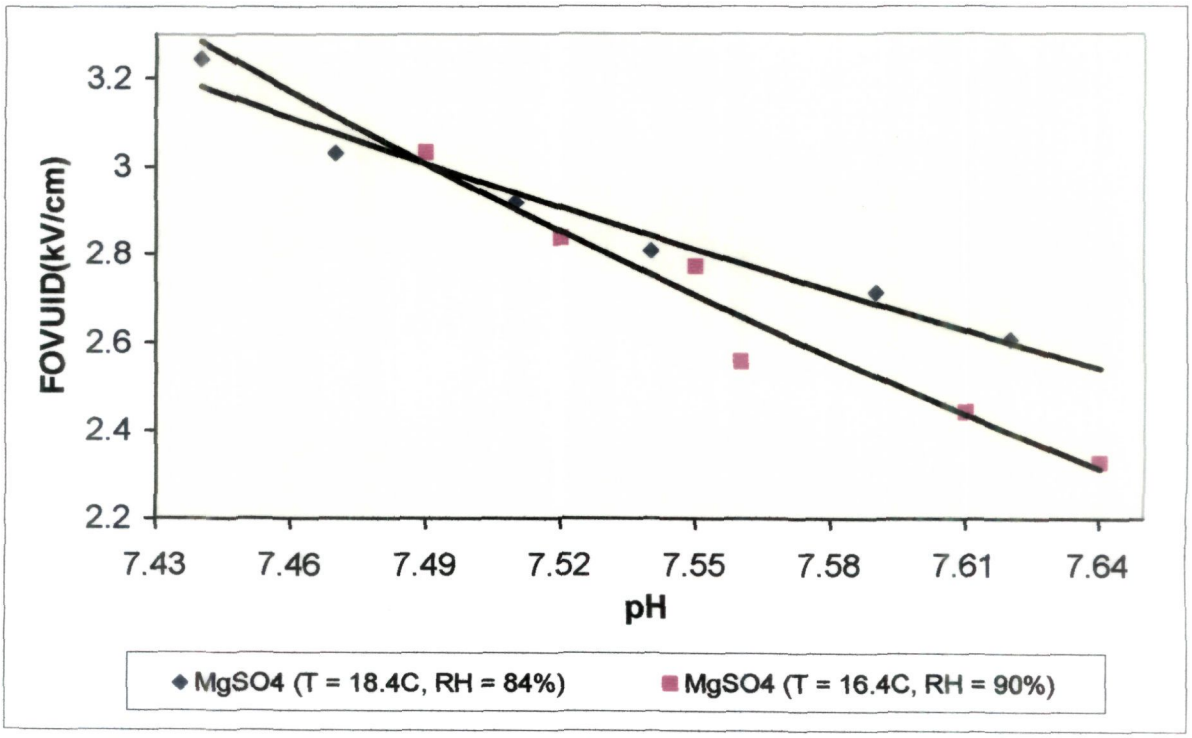


Fig. 4.116: FOVUID vs pH Curve for $MgSO_4$ at different temperature and relative humidity.

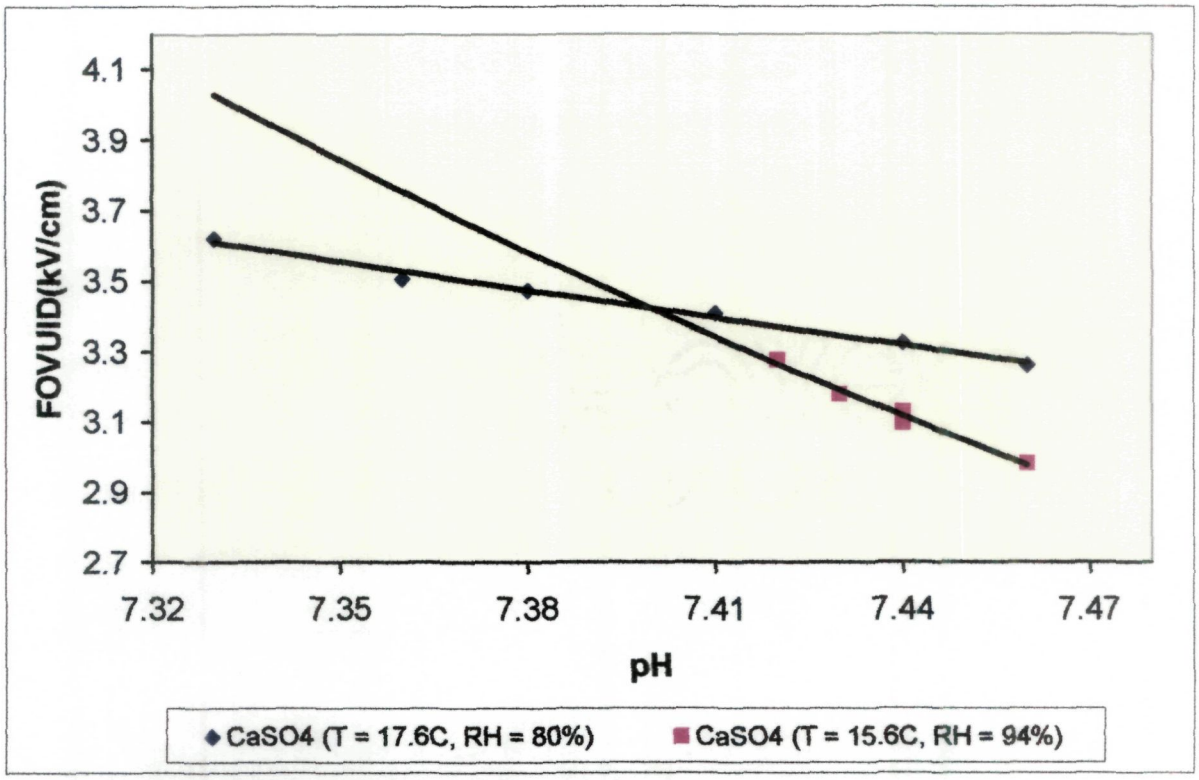


Fig. 4.117: FOVUID vs pH Curve for $CaSO_4$ at different temperature and relative humidity.

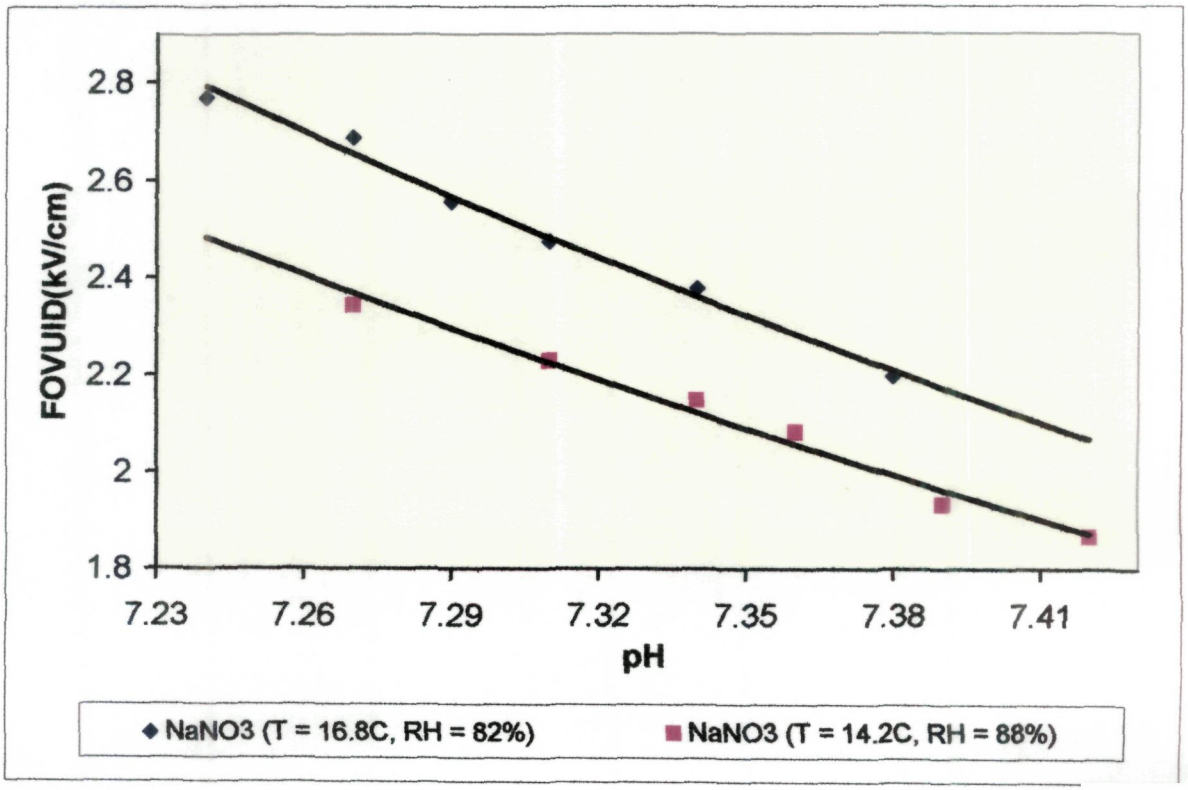


Fig. 4.118: FOVUID vs pH Curve for $NaNO_3$ at different temperature and relative humidity.

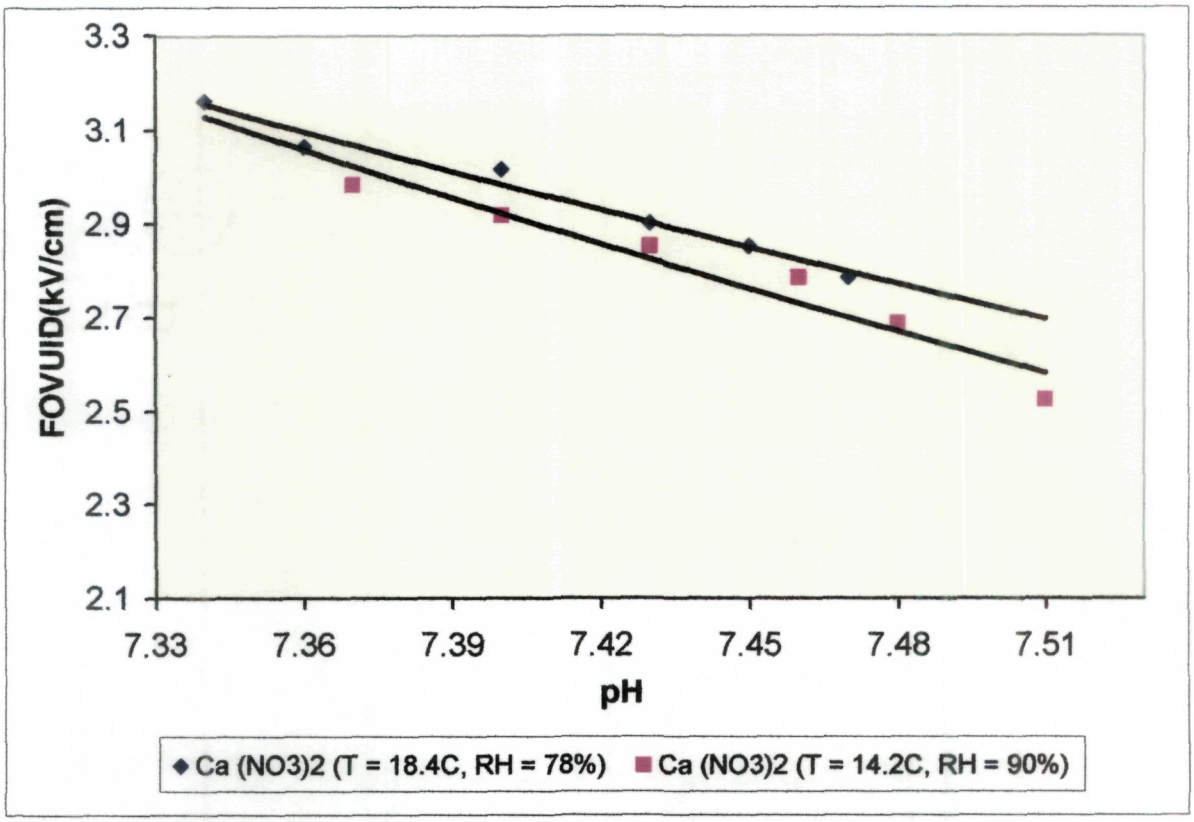


Fig. 4.119: FOVUID vs pH Curve for Ca $(NO_3)_2$ at different temperature and relative humidity.

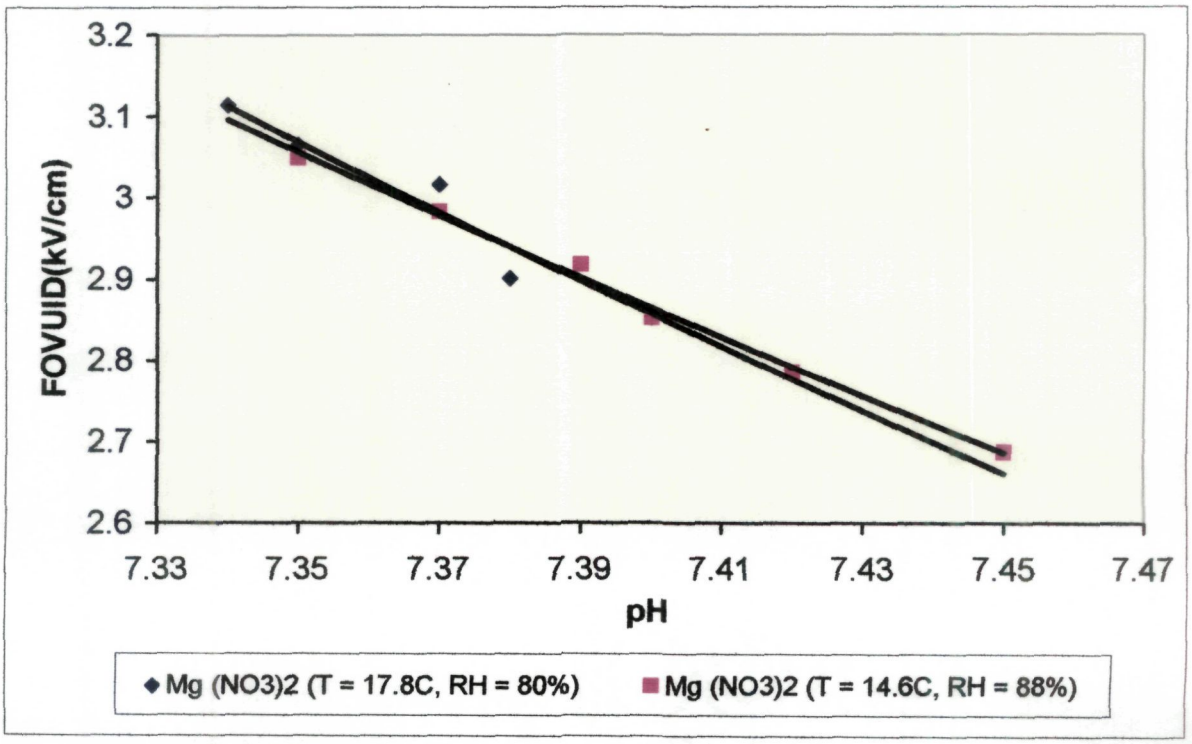


Fig. 4.120: FOVUID vs pH Curve for Mg $(NO_3)_2$ at different temperature and relative humidity.

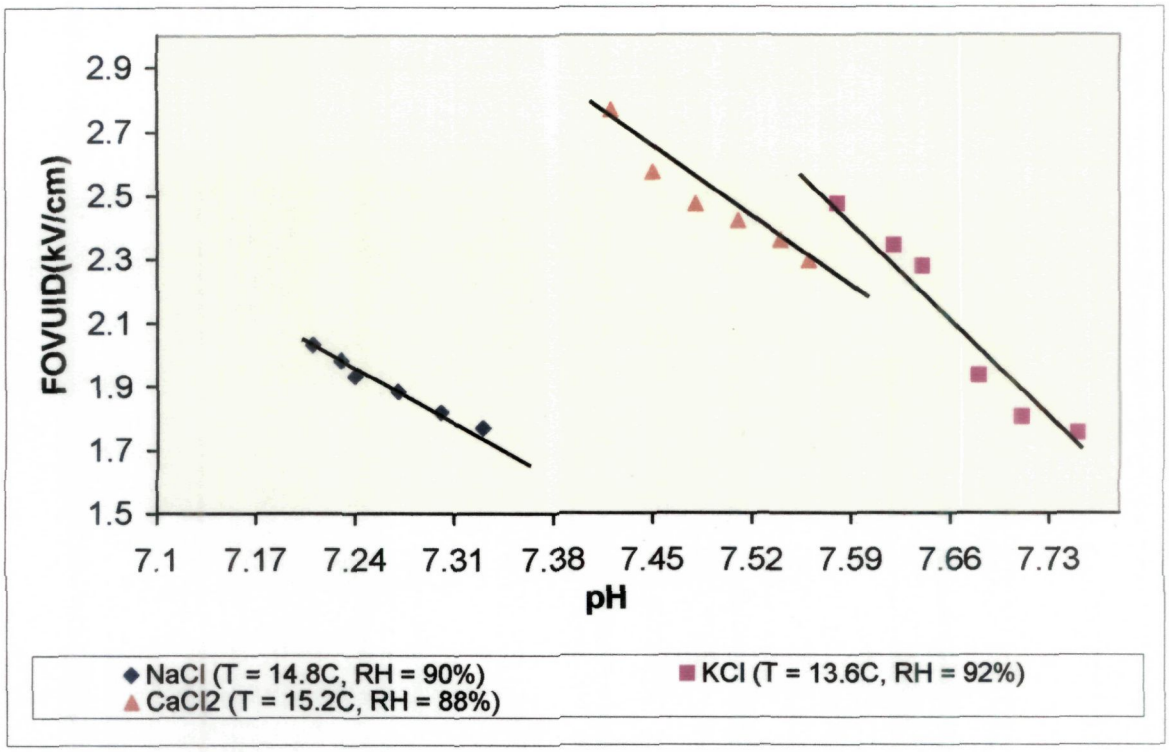


Fig. 4.121: FOVUID vs pH Curve for Chlorides.

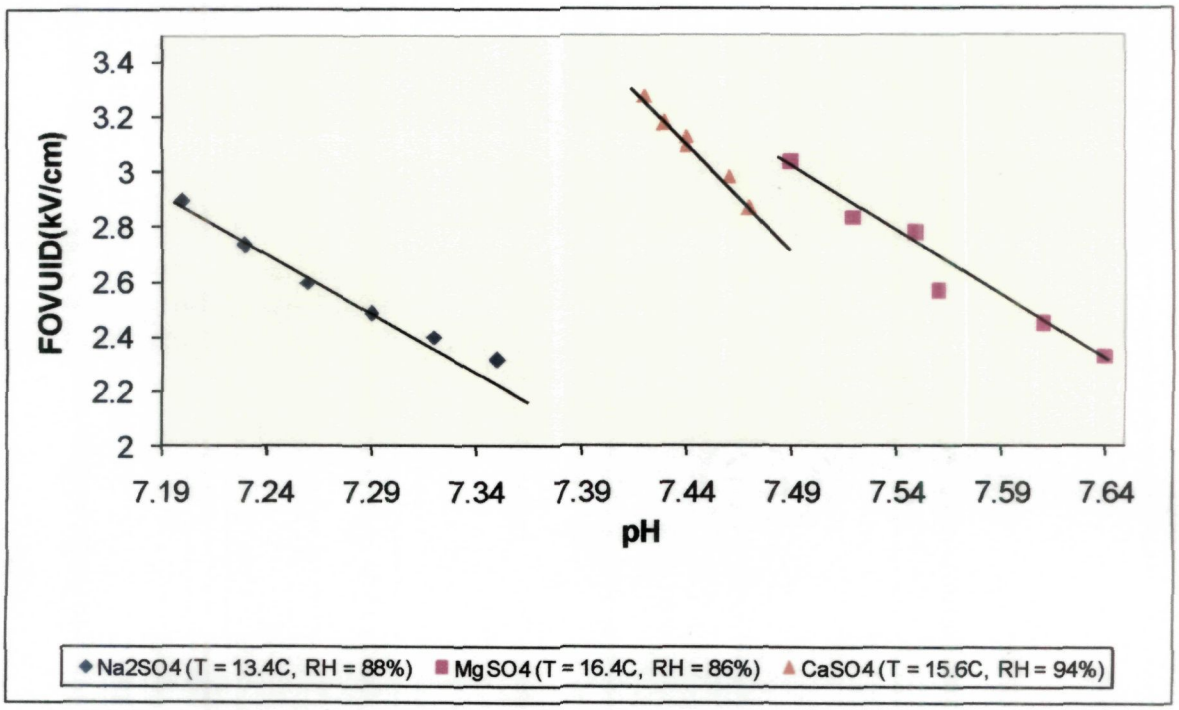


Fig. 4.122: FOVUID vs pH Curve for Sulphates.

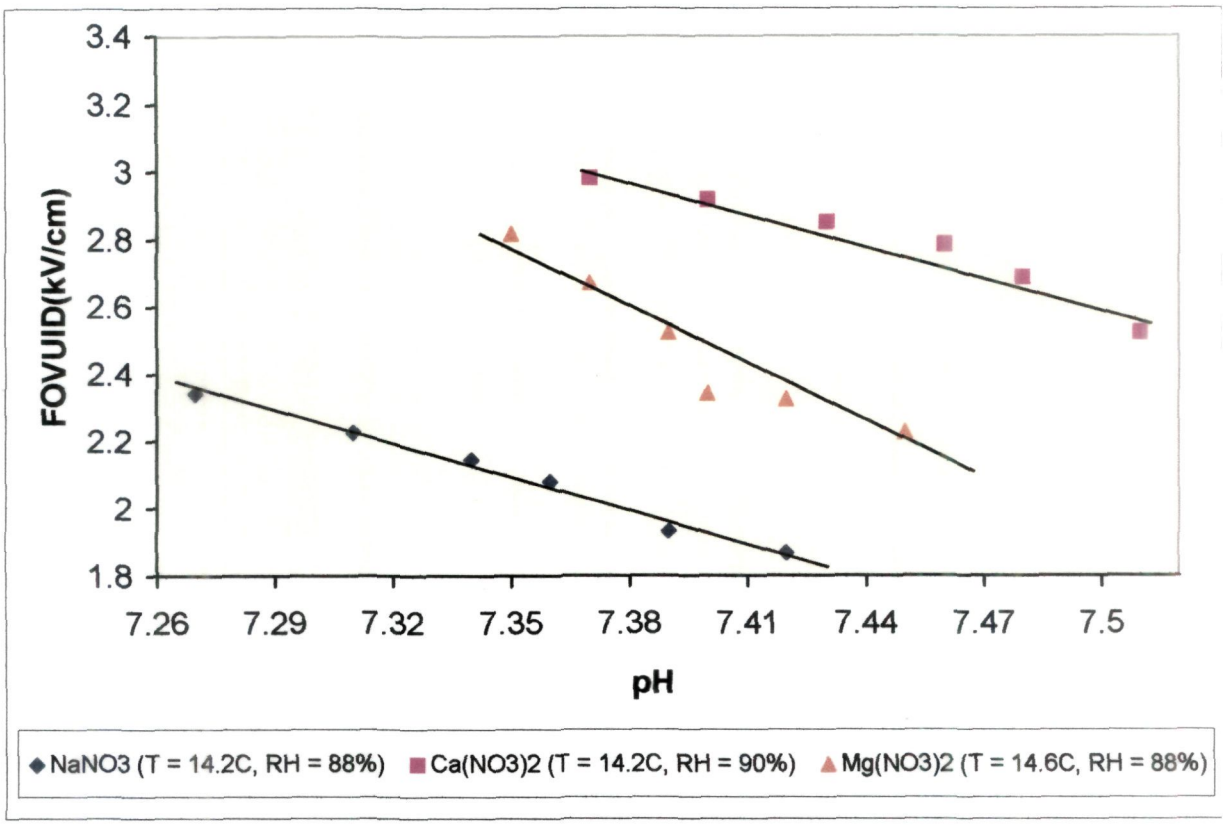


Fig. 4.123: FOVUID vs PH Curve for Nitrates.

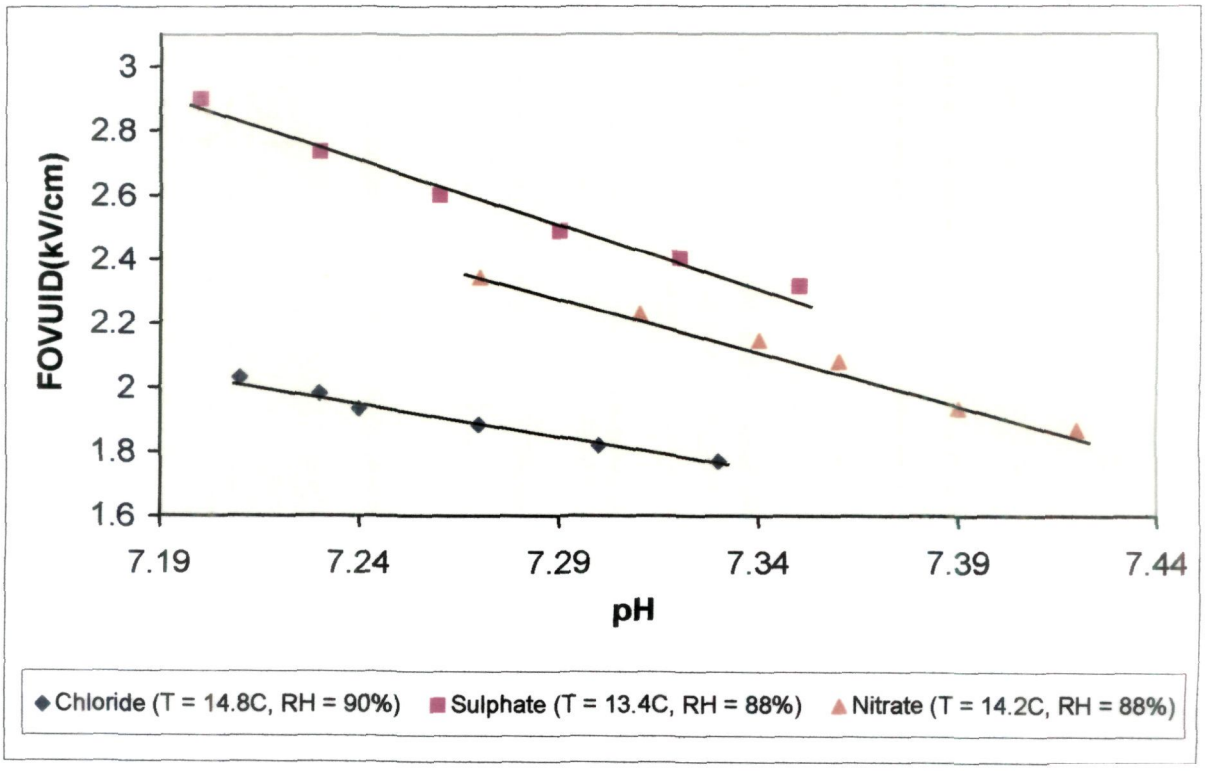


Fig. 4.124: FOVUID vs pH Curve for Na^+ Cation and different anions

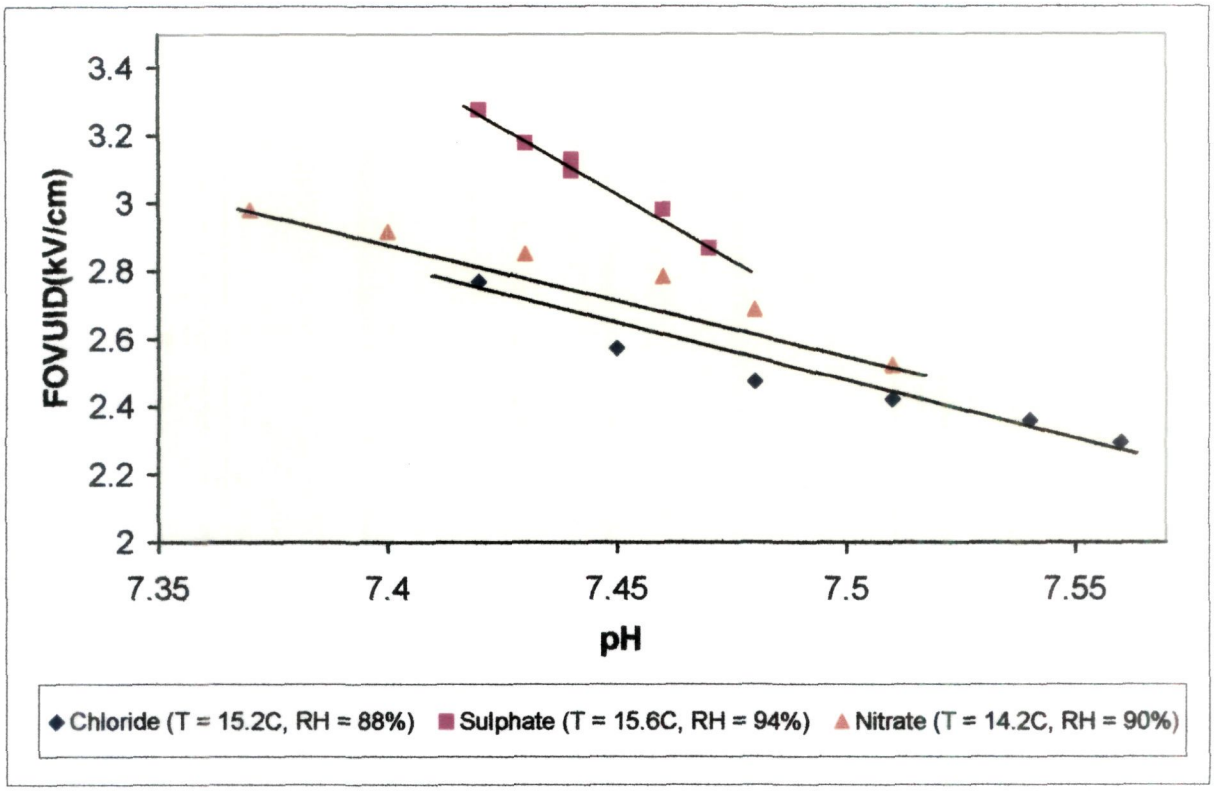


Fig. 4.125: FOVUID vs pH Curve for Ca^{2+} Cation and different anions

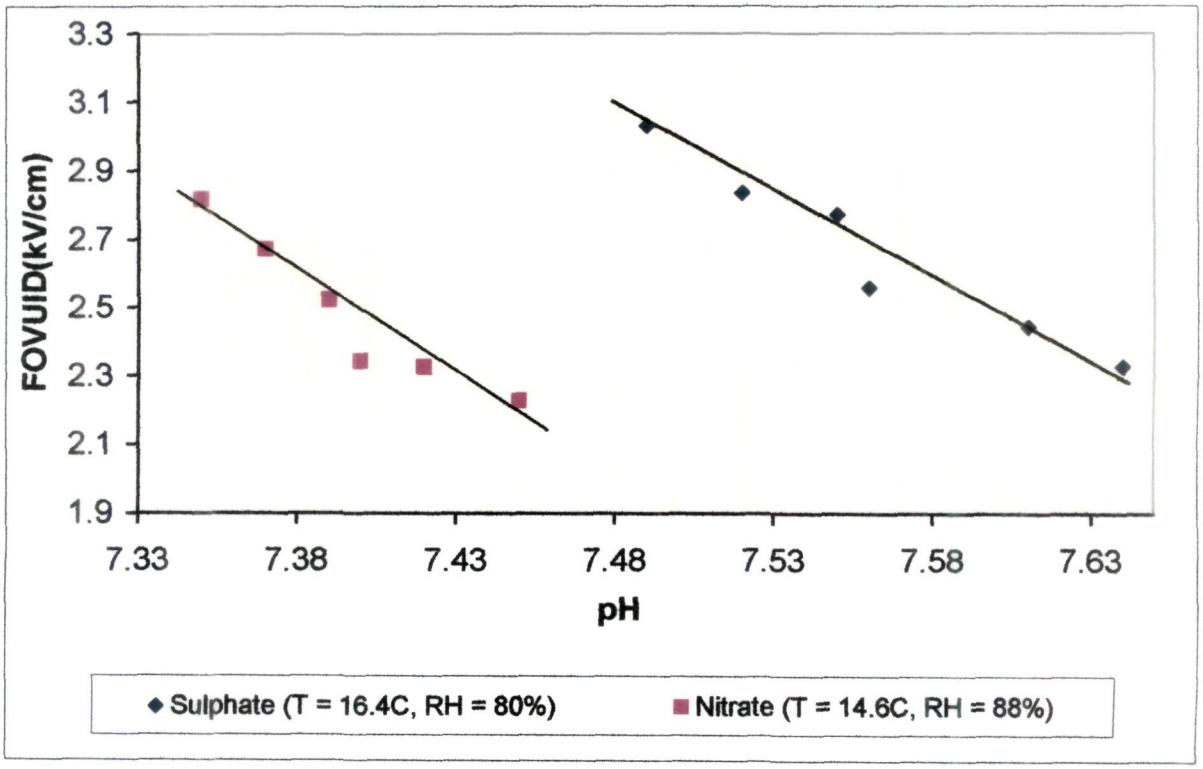


Fig. 4.126: FOVUID vs pH Curve for Mg^{2+} Cation and different anions

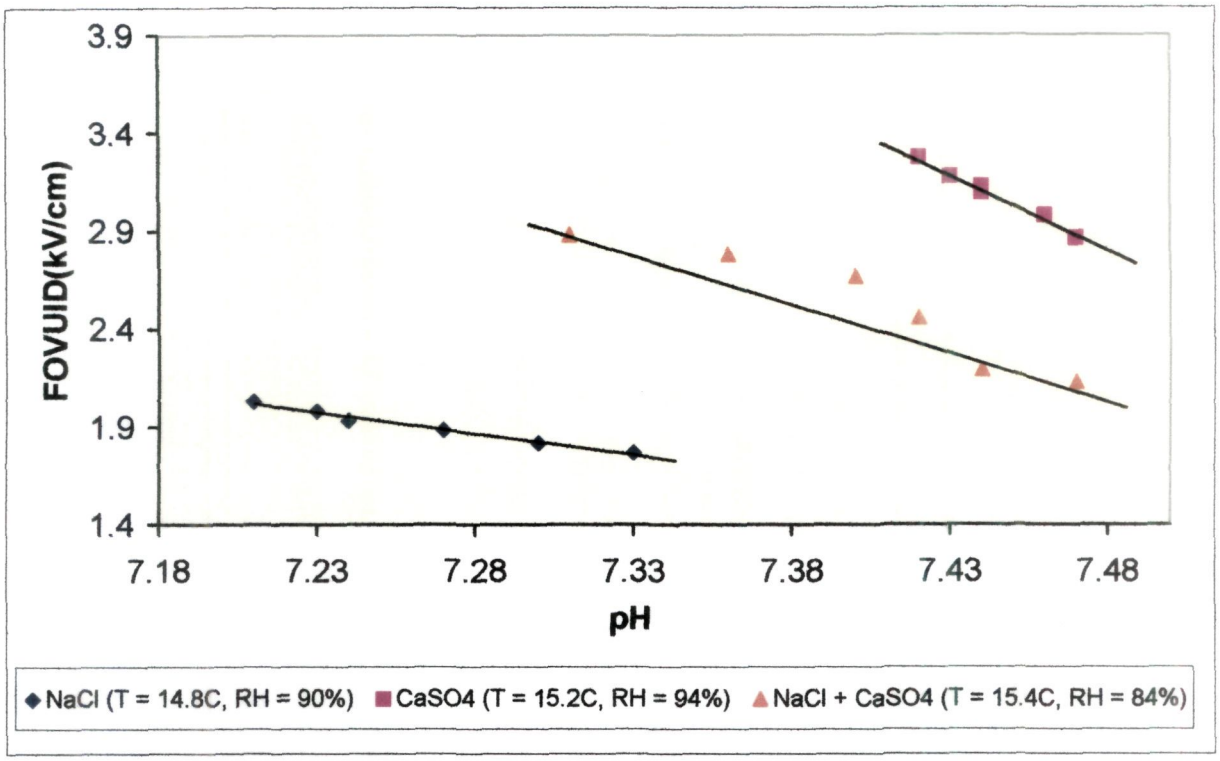


Fig. 4.127: FOVUID vs pH Curve for Single and Double Salts.

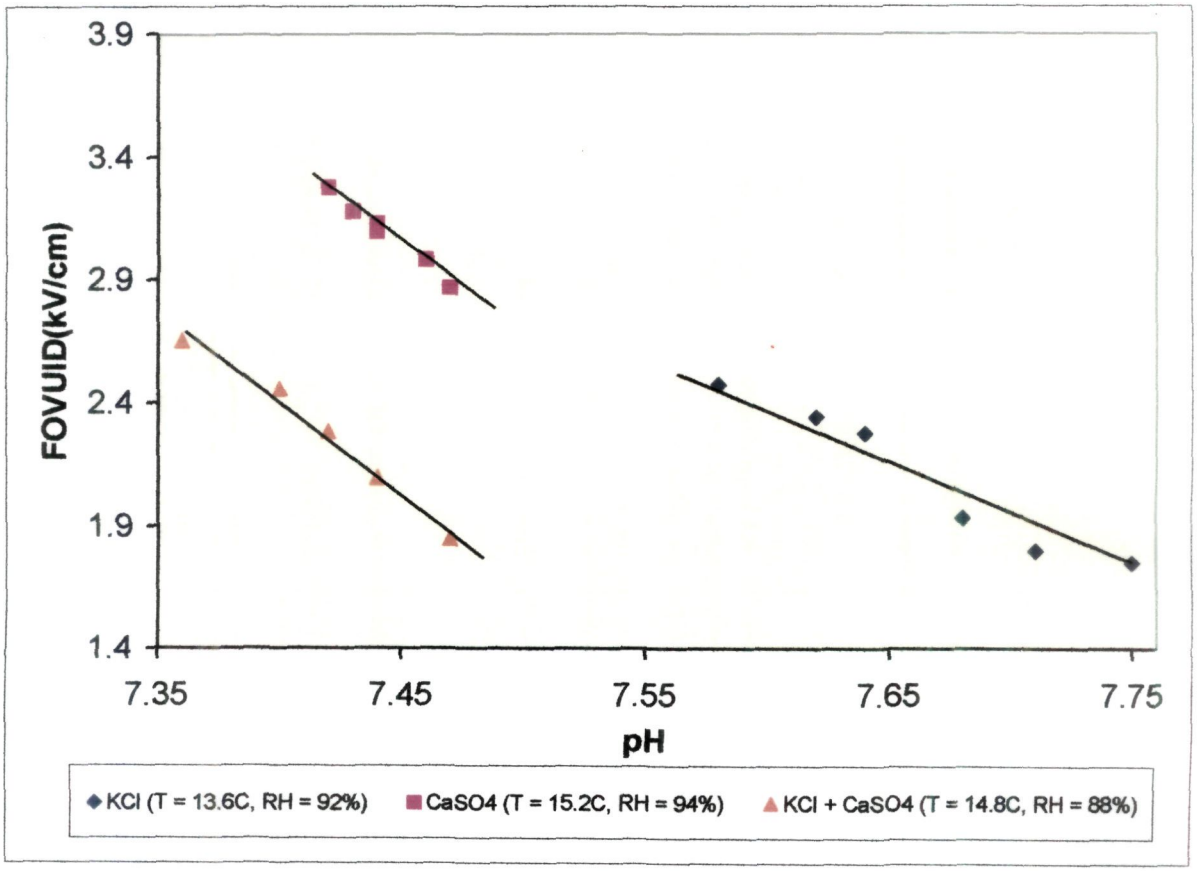


Fig. 4.128: FOVUID vs pH Curve for Single and Double Salts

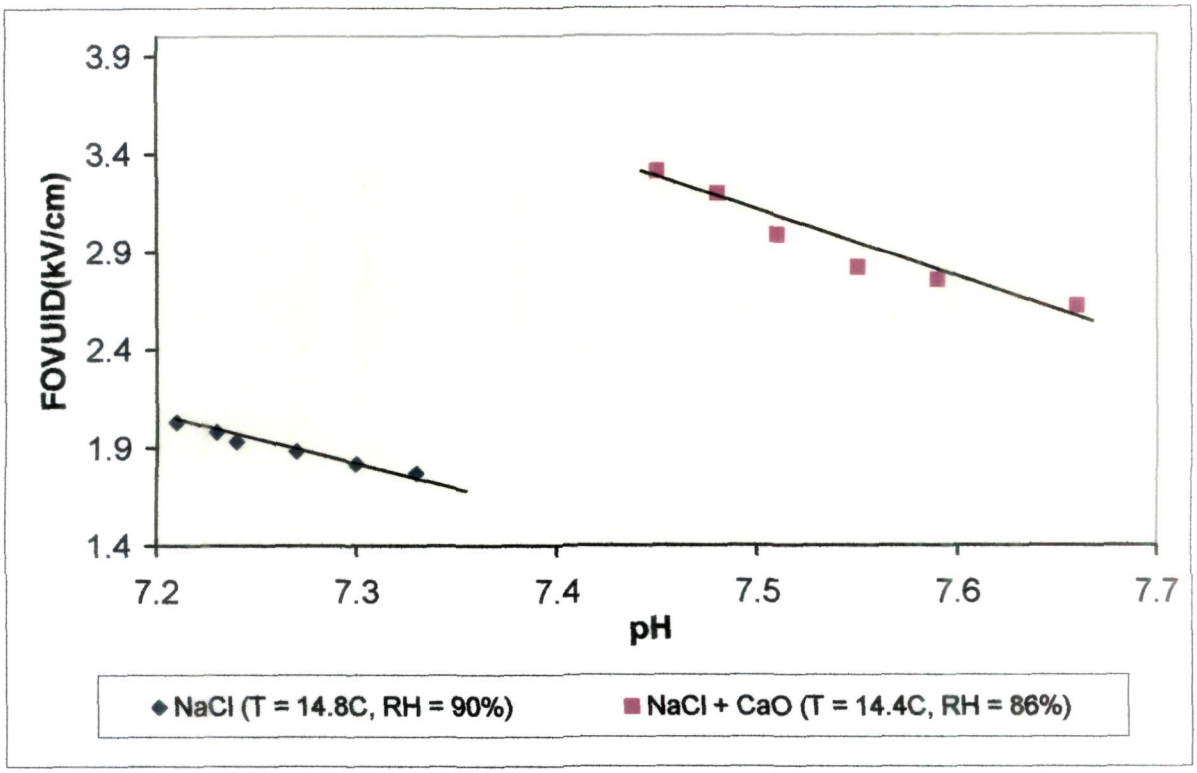


Fig. 4.129: FOVUID vs pH Curve for Single and Double Salts.

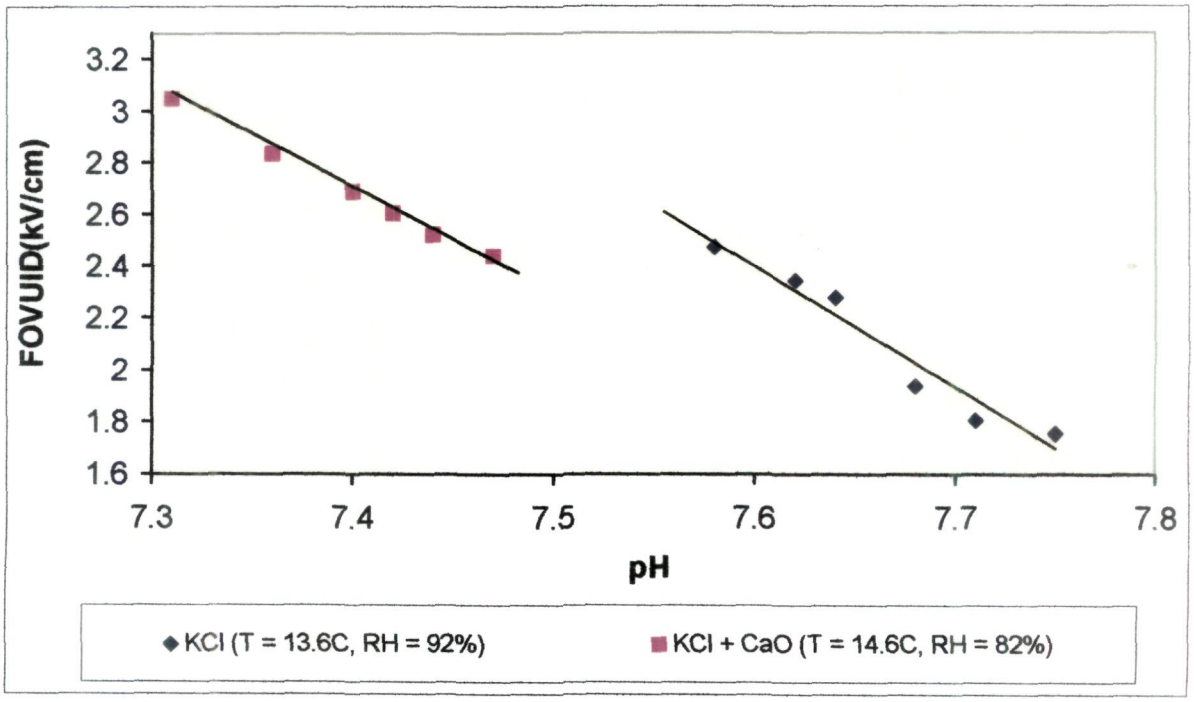


Fig. 4.130: FOVUID vs pH Curve for Single and Double Salts.

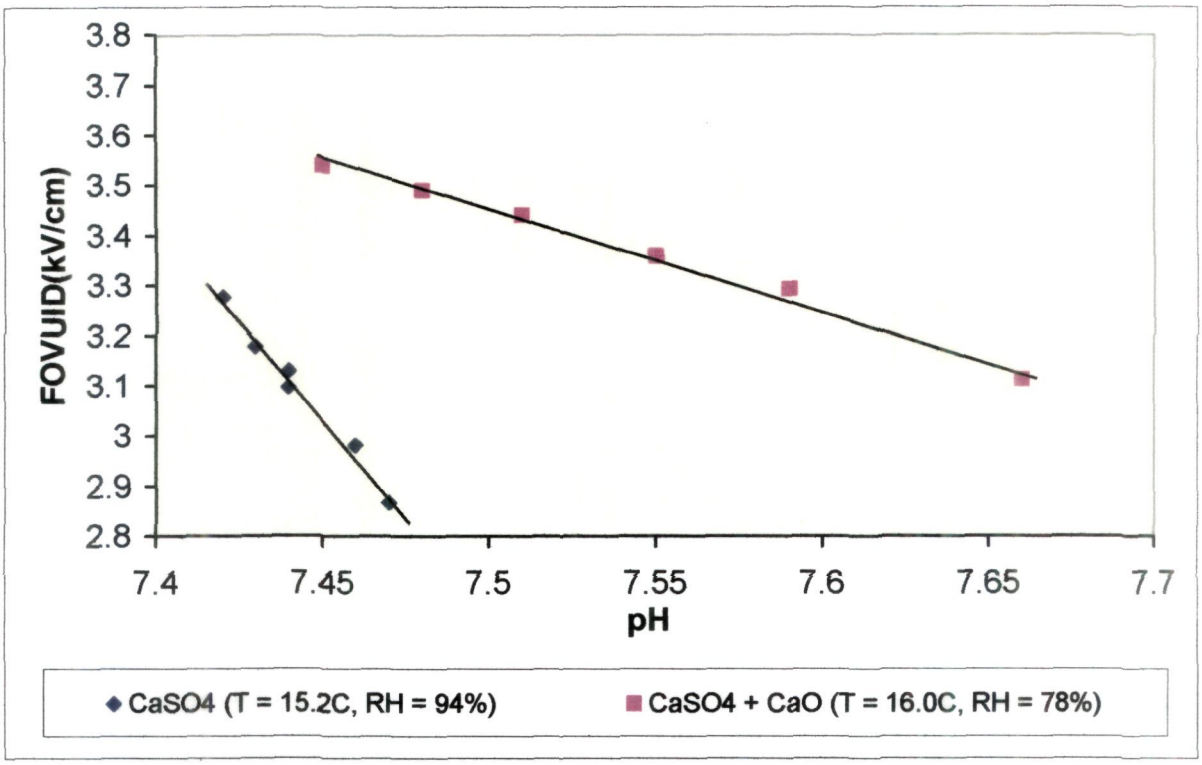


Fig. 4.131: FOVUID vs pH Curve for Single and Double Salts.

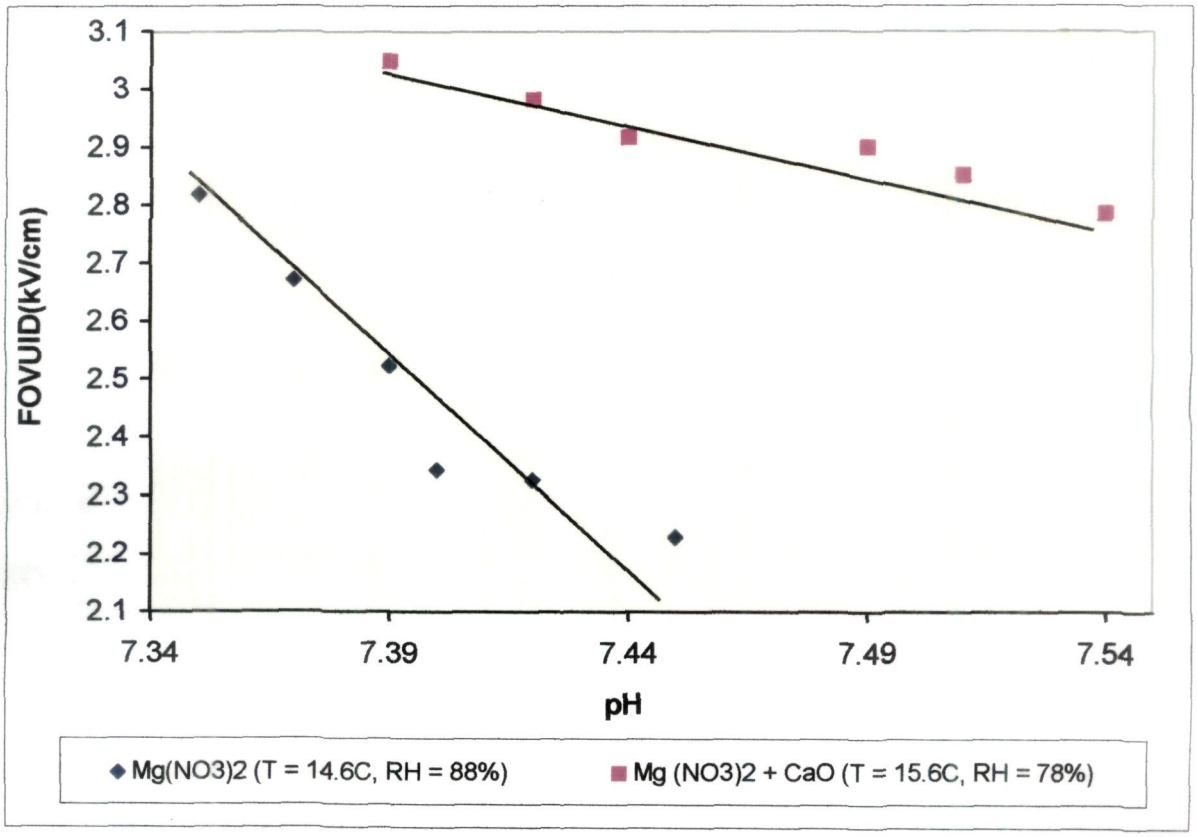


Fig. 4.132: FOVUID vs pH Curve for Single and Double Salts.

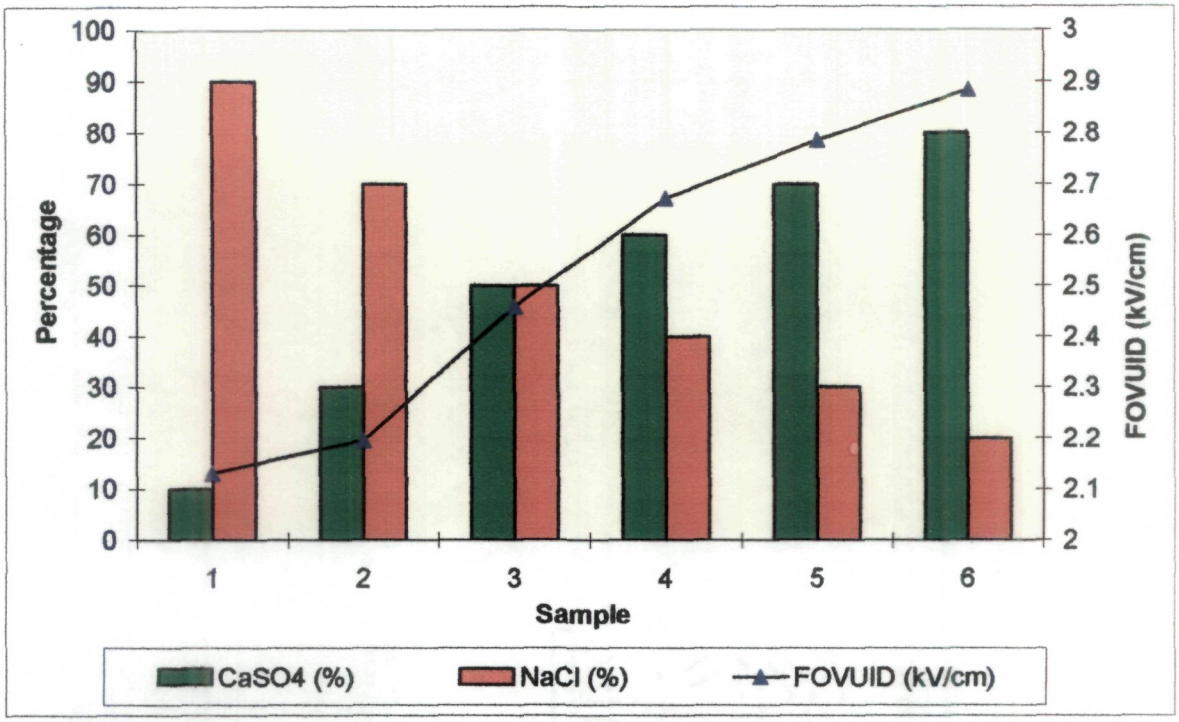


Fig. 4.133 Bar Chart showing variation of FOVUID with % age of NaCl &$CaSO_4$

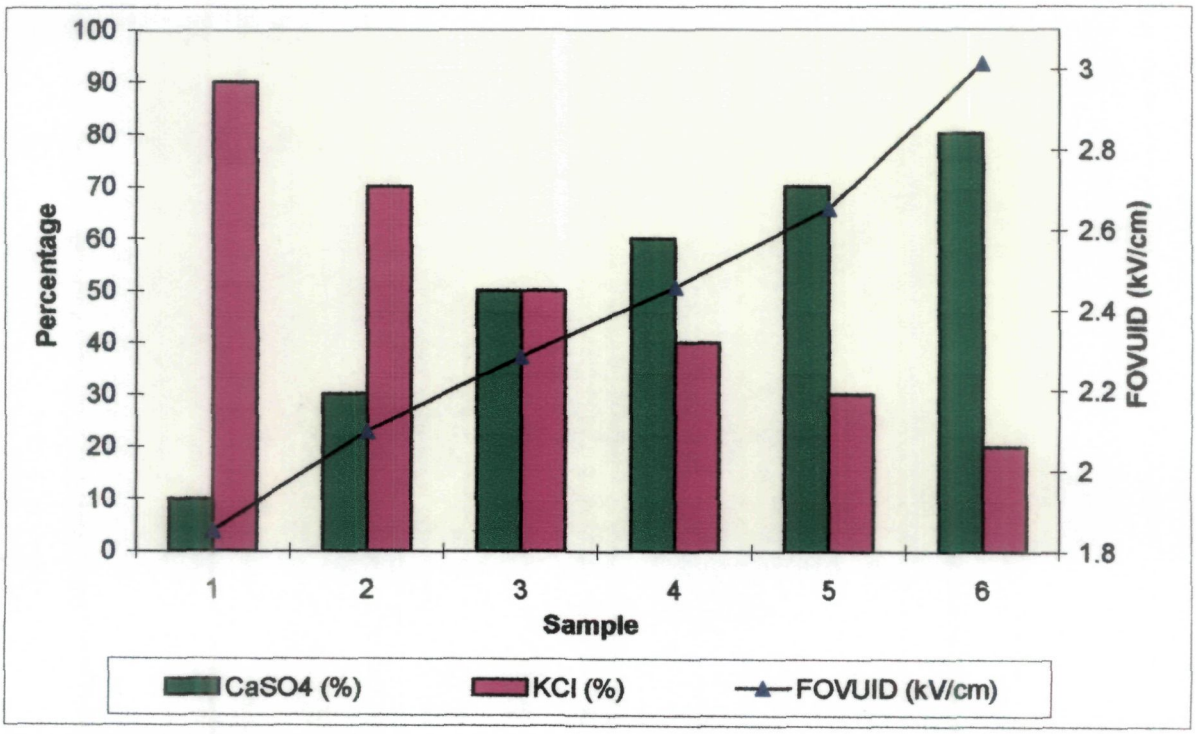


Fig. 4.134 Bar Chart showing variation of FOVUID with % age of KCl &$CaSO_4$

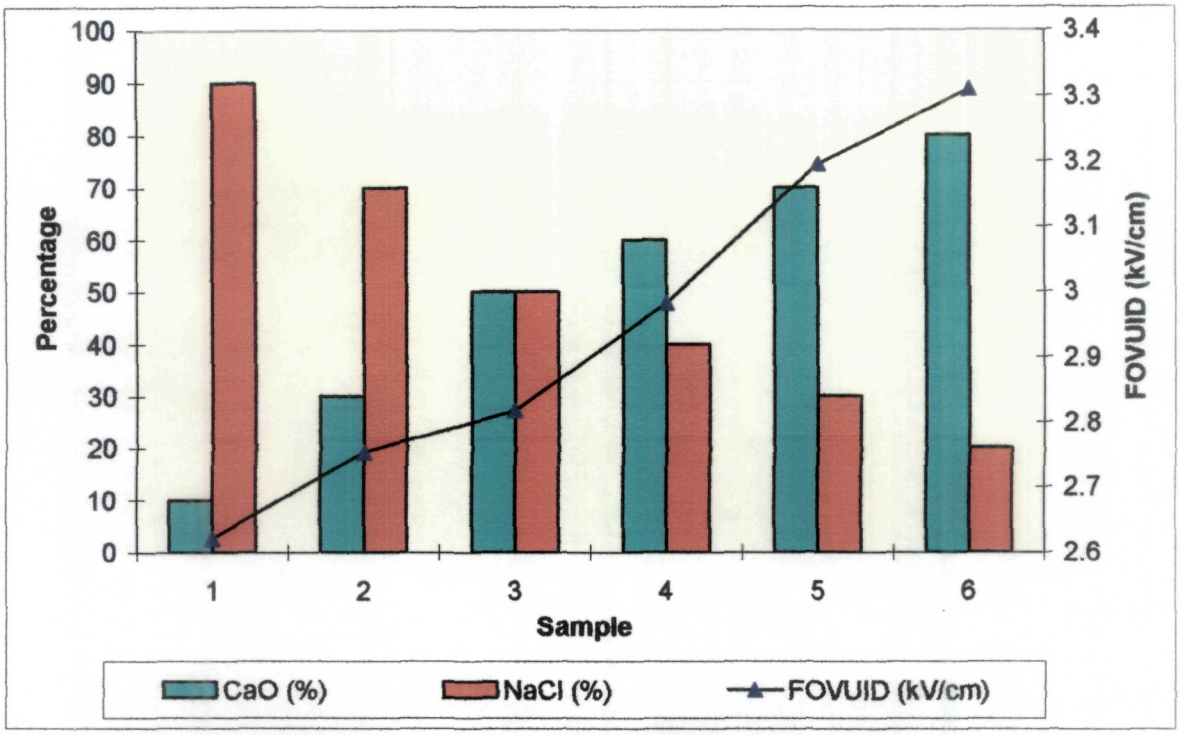


Fig. 4.135 Bar Chart showing variation of FOVUID with % age of NaCl &CaO

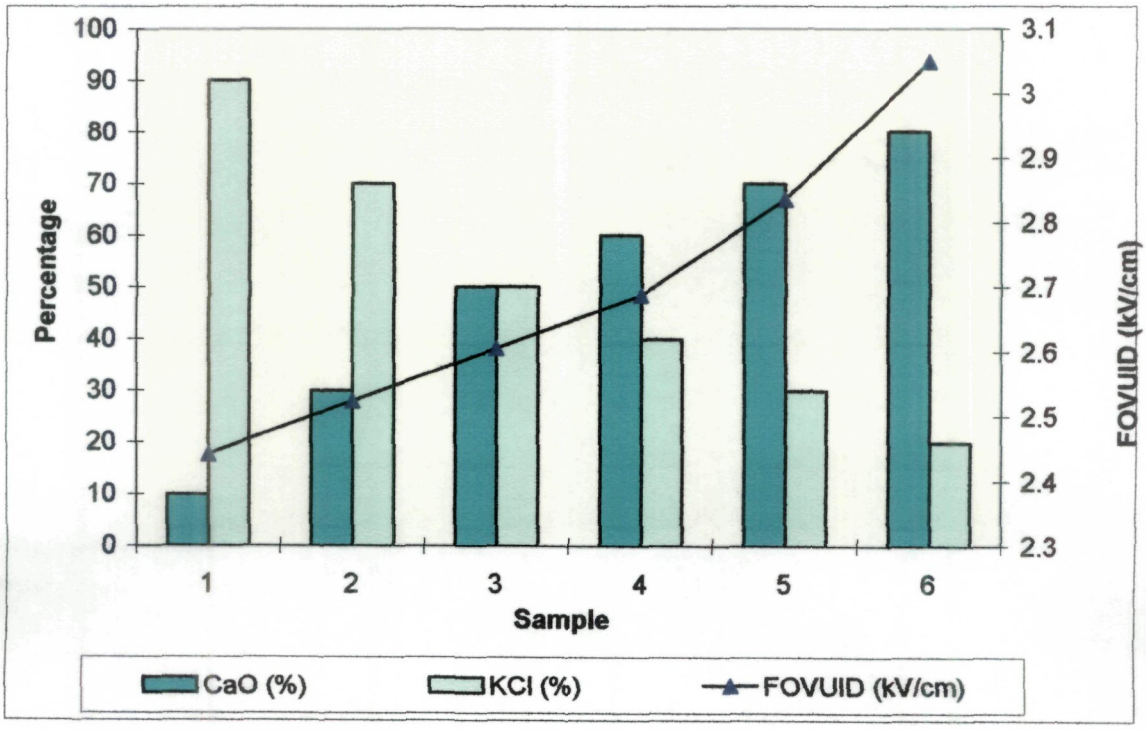


Fig. 4.136 Bar Chart showing variation of FOVUID with % age of KCl &CaO

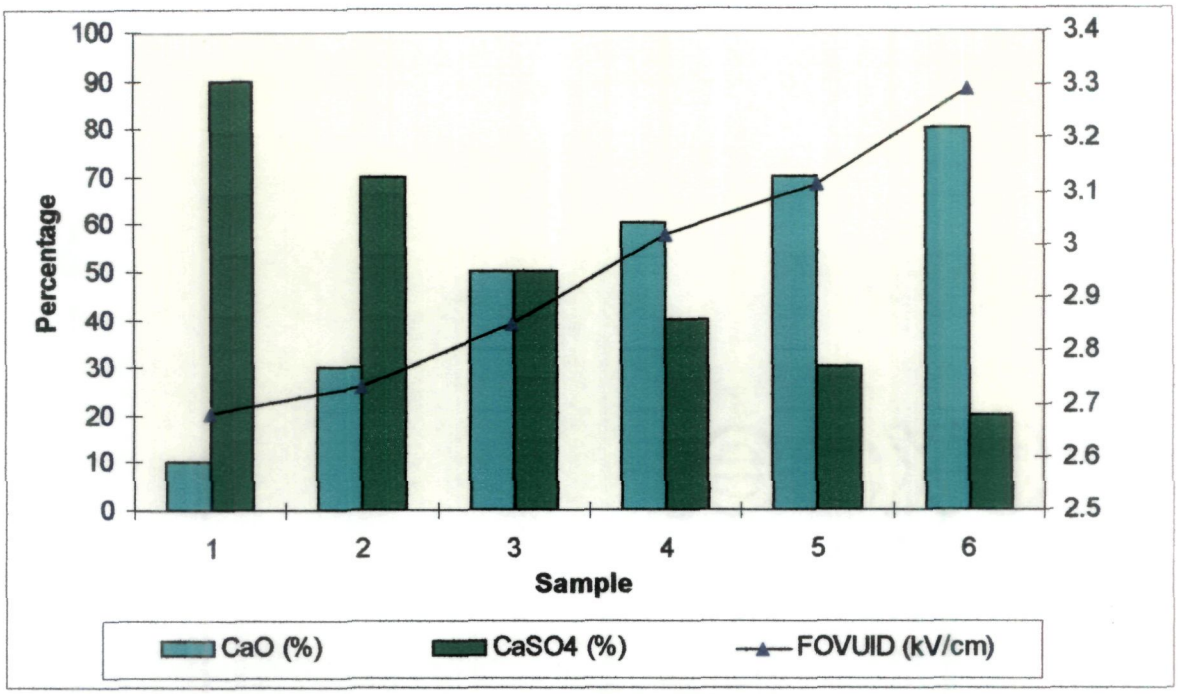


Fig. 4.137 Bar Chart showing variation of FOVUID with % age of $CaSO_4$ &CaO

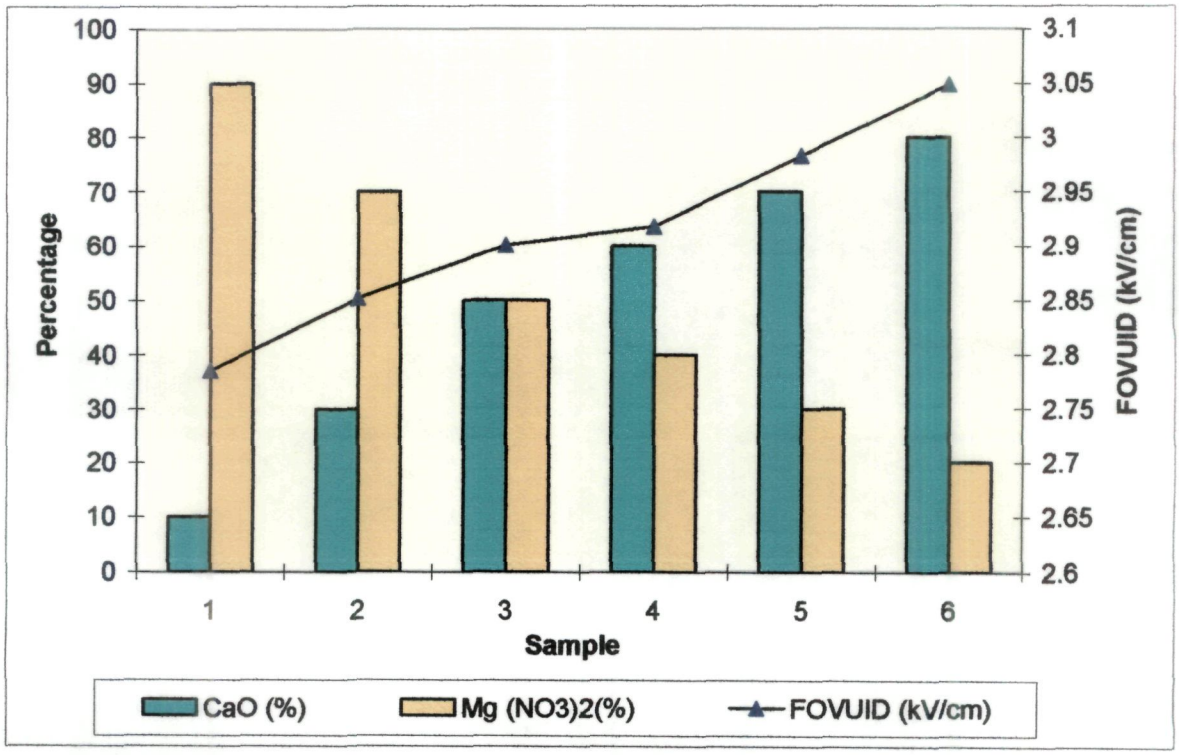


Fig. 4.138 Bar Chart showing variation of FOVUID with % age of Mg $(NO_3)_2$ & CaO

Chapter-5

Discussion

Discussion

In the preceding chapter the experimental results of work done as per the work plan detailed in chapter 2 has been reported. The pollution severity to which an insulator is exposed have since long been assessed by conductivity and ESDD measurement (section 3.7). In addition to these indicators, **in the present work, pH has also been suggested as an indicator of pollution severity.** In this chapter detailed analysis of the results obtained is presented. The dependence of these indicators on the performance of porcelain disc insulators exposed to natural pollution and natural wetting is presented. Efforts have been made to explain the characteristics obtained for insulator performance in and around the city of Aligarh. In addition to natural test, tests under artificial pollution-natural wetting were done and the characteristics obtained have been explained on the basis of detailed chemical analysis of the pollutant. **The effect of ionic radii, hydrated radii, hydration energy, lattice energy, solubility, transportation number, atomic mass, molecular mass and activity coefficient of ions have been identified as the reasons for the different behavior of a particular pollutant vis-à-vis flashover performance of porcelain insulators.** This chapter has been divided into three sections,

A. Natural test analysis

B. Artificial test analysis and

C. Proposed model.

Section A: DISCUSSION ON NATURAL TEST

As already discussed, the three sites of installation differ widely in their environment, although being situated in the same district and only separated by distance of about 25 km. Since the sites differ in the surrounding owing to presence of highway, thermal plant and residential area, the deposits that are present on the insulators have different pH and conductivity, thereby different ESDD and thus influence the resulting characteristics.

Figures 4.1– 4.6 show the variation of FOVUID, WSVUID with ESDD for test insulators installed on a location adjacent to a busy national highway (NH-91) that connects Delhi to industrial town of Kanpur. It is observed that the pollution level as given by ESDD ranges from 0.0304 – 0.0546 mg/cm^{2,} i.e. falling in the light pollution severity range **[95].** It is to be noted that the drop, due to natural wetting, in FOVUID varies between 8 -20 % and the drop in WSVUID varies between 32- 40%.

Figures 4.7 – 4.12 show the variation of FOVUID, WSVUID with ESDD for test insulators installed on a location adjacent to a coal based thermal power plant. It is observed that the pollution level as given by ESDD ranges from 0.0436 – 0.0642 mg/cm^{2,} i.e. falling in the light to medium pollution severity range **[95].** It is to be noted that the drop, due to natural wetting, in FOVUID varies between 14-27 % and the drop in WSVUID varies between 14-43%.

Figures 4.13 – 4.18 show the variation of FOVUID, WSVUID with ESDD for test insulators installed in a residential area of Nishat Apartments. It is observed that the pollution level as given by ESDD ranges from 0.0261– 0.0422 mg/cm^2, i.e. falling in very light to light pollution severity range **[95].** It is to be noted that the drop, due to natural wetting, in FOVUID varies between 17-21% and the drop in WSVUID varies between 15- 36%.

Figures 4.28 – 4.33 show the variation FOVUID, WSVUID with pH for test insulators installed on a location adjacent to a busy national highway (NH-91).

Figures 4.34 – 4.39 show the variation of FOVUID, WSVUID with pH for test insulators installed on a location adjacent to a coal based thermal power plant.

Figures 4.40 – 4.45 show the variation of FOVUID, WSVUID with pH for test insulators installed in a residential area of Nishat Apartments.

5.1 Effect of ESDD and weather conditions on insulators installed at the same site

As detailed in chapter 2, the exposure period for 5 set of samples was 4 months. One sample was tested after exposure period of one year from December 2006 to December 2007. By increasing the exposure period, the samples were subjected to complete cycle of climatic conditions of Aligarh i.e. hot and dry summer with mean temperature between 32.2-33.8°C, mean winter temperature range of 12.2-15.0°C and also to intermittent rainy season with an annual average rainfall of around 850mm.

Figure 4.19 shows a comparative graph that shows the variation in FOVUID with ESDD of samples installed at NH-91(location 1) for different months during the period of study. It is observed that the build of pollution deposit from July to December 2005 is translated into ESDD in the range 0.0422 - 0.0486 mg/cm^2 and the corresponding drop in FOVUID is about 15% for test in December 2005 (RH range 40-46%). During the period December 2005- March 2006 a slight decrease in ESDD is observed, probably owing to winter rain that occurs generally in last week of December and January in this area. The fall in FOVUID values was about 10% due to decreased ESDD and low RH of 28-32%.

During the period March 2006-July 2006, for location 1, it is observed that ESDD values have fallen about 30% because of light rains that occur intermittently during the period June-July. Nonetheless in spite of this decrease in ESDD, for tests done in July 2006, FOVUID values fall by about 13% due to high RH of 65-70%. For the period July 2006- December 2006 the ESDD values are lesser due to cleaning of insulators with monsoon rains and also due to low values of RH in December 2006, the fall in FOVUID is almost 09%.The tests discussed were done at interval of 4 months, a sample was also subjected to exposure period of 1 year from December 2006 to December 2007. After this exposure the pollution deposit was higher by

about 20% than that of December 2006 values, also owing to slightly higher RH of about 40%, the FOVUID values fell by about 15%.

Figure 4.20 shows a comparative graph that shows the variation in FOVUID with ESDD of samples installed at site near a thermal power plant (location 2) for different months during the period of study. It is observed that the build of pollution deposit from July to December 2005 is translated into ESDD in the range 0.0532 - 0.0620 mg/cm^2 and the corresponding drop in FOVUID is about 22% for test in December 2005 (RH range 42-48%). During the period December 2005- March 2006 a slight increase in ESDD is observed, in spite of light winter rain, probably the pollution deposits created by the thermal plant were more. It is to be noted that increase in fly ash concentration increases the water hold capacity of deposits, pH, conductivity and also increase in sulphate, carbonate, bicarbonate and other metal ions **[123].** The fall in FOVUID values was about 21% due to increased ESDD.

During the period March 2006-July 2006, for location 2 it is observed that ESDD values have fallen about 15% because of rains that occur intermittently during the period June-July. Nonetheless in spite of this decrease in ESDD, for tests done in July 2006, FOVUID values fall by about 26% due to high RH of 68-76%. For the period July 2006- December 2006 the ESDD values are lesser due to cleaning of insulators with monsoon rains, but because of high RH in December 2006, the fall in FOVUID is almost 22%. The tests discussed were done at interval of 4 months; a sample was also subjected to exposure period of 1 year from December 2006 to December 2007. After this exposure the pollution deposit were higher than that of December 2006 values, again due to the reason of high pollution created by thermal plants but owing to slightly lower RH of about 36-44%, the FOVUID values fell by about 15%.

Figure 4.21 shows a comparative graph that shows the variation in FOVUID with ESDD of samples installed at site in Nishat

Apartments (location 3) for different months during the period of study. It is observed that the build up of pollution deposit from July to December 2005 is translated into ESDD in the range 0.0388 - 0.0395 mg/cm^2 and the corresponding drop in FOVUID is about 20% for test in December 2005 (RH range 40-46%). During the period December 2005- March 2006 ESDD is almost same as was for the previous quarter, RH also lies in the range 28-32 % and therefore fall in FOVUID values is about 20%.

During the period March 2006-July 2006, for location 3 it is observed that ESDD values have fallen slightly because of light rains that occur intermittently during the period June-July. Nonetheless in spite of this decrease in ESDD, for tests done in July 2006, FOVUID values fall by about 20% due to high RH of 70-78%. For the period July 2006- December 2006 the ESDD values are lesser due to cleaning of insulators with monsoon rains, but because of high RH in December 2006, the fall in FOVUID is almost 18%. For samples that were exposed for 1 year duration (December 2006- December 2007), it is found that the conductivity of deposit for December 2007 samples was somewhat higher than December 2006 values. correspondingly ESDD is also higher. This higher ESDD in conjunction with higher RH of about 42% leads to about 20% lower values of FOVUID.

It is worth mentioning that the maximum drop in WSVUID and FOVUID values are for the samples tested in March 2008. This may be due to the reason that during the period December 2007 and March 2008 normal winter rains did not occur; thereby self cleaning of insulator surface did not happen leading to substantial deposits on the insulator. Apart from this, the relative humidity was very high during the first week of March 2008 and unusual fog conditions prevailed on 6th, 7th and 8th March 2008, the days when testing of samples was done **[124]-[127]** (Appendix A-5). Thus in addition to high ESDD, higher values of relative humidity plays a vital role in lowering the voltage at which the insulator flashes over.

5.2 Effect of installation site of insulators

From figures 4.22 – 4.27 it is observed that out of the three sites, as per ESDD values, Nishat Apartment (located in residential area) is relatively least polluted, NH-91 site moderately polluted and thermal plant site relatively highly polluted. The fall in FOVUID values are smallest for Nishat Apartment site. It is also observed that in spite of thermal plant samples showing higher ESDD for the entire test, the FOVUID values are almost similar to that of NH-91. This is probably due to the characteristics of the inert ash deposited on the samples; this ash forms an inert matrix and impedes the flow of leakage current. From the foregoing discussion it is clear that in spite of the samples being installed in and around city of Aligarh, separated by about 25 km present a different picture as far as flashover and withstand characteristics are concerned. This is due to the different nature of deposits on insulators installed in a particular site. The deposits on insulators exposed to the three locations are mainly dust. The atmospheric dust consists of solid particles of varied dispersion, which depends on their type and distance from the nearest emitters. Large particles are dominant in the vicinity of emitters, while fine particles are spread by wind. In industrial emission, three type of dust are dominant, those formed by combustion of coal, metallurgical dust, dolomite lime. Non-organized dumps and fly sands are also source of air pollution.

The common content of the dust that prevails in and around Aligarh consists of cations such as Na^+ , K^+ , Ca^{2+} , Mg^{2+} and anions such as HCO_3^- , CO_3^{2-} , Cl^- , NO_3^{2-}, SO_4^{2-} . This may be due to the reason that surface and ground water in Aligarh has presence of above ions **[128].** This leads to presence of these ions in the soil. Due to erosion and transportation by wind, some components of the soil fly off as dust and get dispersed in the environment and may settle on the insulators. Table A-1 (Appendix A-6) gives the content of various ions found in ground water in Aligarh **[129].** Owing to large number of electroplating, lock, hardware industries, seepage

from these metal processing industries and municipal effluents into the ground has lead to alarming levels of heavy metals such as Cd, Cr, Pb, Fe, Cu, Ni, Zn, Mn in the soil and ground water. Due to all the above listed metals and ions, the pH of ground water ranges from 6.9 – 8.2**[130] [131] [132].** Extensive agricultural activity has also led to use of fertilizers that contribute to presence of PO_4^{3-}, NO_3^{2-} . Apart from these common contents in the dust deposits, the locational pollutants are different.

For case of NH-91 with heavy vehicular traffic, it is estimated that the average dust fall rate per unit area per month on this highway at Aligarh is 34.52 gm/m^2 per month **[133] [134].** In addition to above contents of dust, the insulators are also subjected to tiny particles of carbon, ash, oil formed by incomplete combustion of fuel **[135].** It is to also mention that the site of installation on NH-91 was very near to few industries that produce cooking oil and wheat flour. The area also has large agricultural area using variety of fertilizers.

For the case of site near Kasimpur thermal power plant, that runs on 3192 metric tonne of coal/day produces oxides of sulphur, nitrogen and carbon particulates **[136] [137].** In addition to the above contents and that given in the previous paragraphs, the insulators are also subjected to fly ash deposits that consist mainly of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO,P_2O_5 ,carbon and carbonate ions**[138].** Apart from this the area also has number of brick kilns using coal as fuel and large agricultural area using variety of fertilizers. It is to be noted that increase in fly ash concentration increases the water hold capacity of deposits, pH, conductivity and also increase in sulphate, carbonate, bicarbonate and other metal ions **[123].**

For the case of Nishat Apartment, which is a residential area away from main highway, has a very low vehicular traffic and therefore the dust deposit is less than 20 gm/m^2 per month **[133][134].** There is a railway line about 200metres from the site of installation, the train frequency is very low and is run on diesel locomotives. The area does not have any agricultural

fields and as such pollutants arising of fertilizers are not found. Thus the deposits to which the insulators at this site are subjected are the common contents that are listed above.

5.3 Effect of pH

It can be observed from figures 4.28 – 4.45 that as the pH of the deposits increases towards 7 (neutral) there is increase in the WSVUID and FOVUID values. The increase is not substantial because of only slight increase in pH. For difference in pH in the range 0.1 – 0.2 the resulting changes in WSVUID and FOVUID was observed between 5-10%. This may be attributed to the fact that as pH of contaminant approaches 7, the hydrogen ion concentration decreases and the deposits are less acidic and therefore conductivity decreases, leading to higher WSVUID and FOVUID. Since pH is based on log scale, difference of 1 pH leads to change in hydrogen ion concentration by factor of 10.Thus for the a decrease of 0.4 pH, the hydrogen ion concentration increases by a factor of 2.5. These additional ions contribute to the change in FOVUID and WSVUID characteristics. Moreover for higher relative humidity ambient the availability of additional hydrogen ions leads to further lowering of WSVUID and FOVUID values.

It can be observed from figures 4.46 and 4.47 that the pH ranges from 6.52 – 6.92 for samples installed at NH-91 and thermal plant. The deposits are more acidic than deposits of Nishat apartment (figure 4.48) due to the difference in the contents of deposits. The contents listed in section 5.2 are responsible for forming acidic nature of deposits. Although the ground water in Aligarh is alkali bicarbonate (pH > 7), it is observed that pH of ground water around NH-91 is 7.12, that near thermal plant around 6.98 and that around Nishat Apartment it is 7.22. This difference in pH of groundwater will naturally affect the pH of the aqueous dust solution in these areas. Apart from this SO_X and NO_X produced from combustion of coal and hydrocarbons combine with atmospheric moisture and form acidic deposits

on the samples. Near the thermal plant fly ash adsorbs these gases and with interaction with natural wetting condition produces corrosive acids and thus results in lower pH of these deposits..

Figures 4.49 – 4.54 shows variation in FOVUID with pH for the three sites. It is observed that samples installed at NH-91 and thermal plant have lower value of FOVUID than Nishat Apartment. This may be attributed to the presence of contents as detailed in section 5.2. These contents alongwith SO_X and NO_X lead to such a characteristics.

Section B: DISCUSSION ON ARTIFICIAL TEST

It has already been discussed in section 1.2 and 3.2 about occurrence of certain salts at different locations. The salts detailed were used as contaminant for study of insulator behaviour. Since dry salts pose no serious threat as far as electrical behaviour is concerned, wetting of these salts do seriously alter the electrical performance. In the applied methodology wetting process was not done artificially but was done by exposing the artificially contaminated insulator to natural wetting condition. Thus the method used may be suitably termed as a **semi-natural method of testing** rather than artificial testing method.

Single Salt as Contaminant

The sample insulators were coated with single salts namely NaCl, KCl, $CaCl_2$, $MgSO_4$, $CaSO_4$, Na_2SO_4, $NaNO_3$, Mg $(NO_3)_2$ and Ca $(NO_3)_2$. The salts taken for the study can also be classified as Univalent salts such as NaCl, KCl, Na_2SO_4, $NaNO_3$ and Bivalent salts such as $CaCl_2$, $MgSO_4$, $CaSO_4$ Mg $(NO_3)_2$ and Ca $(NO_3)_2$. The withstand voltage per unit insulation distance (WSVUID) and flashover voltage per unit insulation distance (FOVUID) have been tabulated in the previous chapter for different conductivity, ESDD and pH. This section deals with the analysis of the obtained results on the basis of chemistry of the salts.

5.4 Variation of WSVUID, FOVUID on ESDD

Figures 4.55 to 4.72 gives variation of WSVUID and FOVUID with ESDD for different salts at different temperature, pressure and relative humidity. It can be observed that at higher temperature and low relative humidity the percent change in WSVUID and FOVUID is less as compared to that at low temperature and high relative humidity.

The reason for the obtained characteristics is due to the dependence of viscosity of water on temperature as well as suspension of more water molecules in atmosphere at high relative humidity. As temperature increases the viscosity of water reduces significantly **[139]** and therefore for a given salinity, the thickness of the contamination layer is comparatively thin due to greater drop-off. Consequently, this leads to a reduced amount of salt in the contaminant layer. It has been reported that flashover characteristics of contaminated insulators are not much deteriorated for relative humidity upto 75% **[88].** For RH > 80%, salts on the insulator surface undergo increased moisture absorption, thereby decreasing the insulation strength of the surface and resulting in flashover. The results obtained in this thesis conform to what has been reported earlier **[7] [88].**

5.5 Variation of FOVUID on ESDD at different ambient conditions

Since the flashover characteristics of an insulator are important for devising proper insulation level, figures 4.73 – 4.81 have been drawn to relate FOVUID with ESDD for all the single salts at different temperature and humidity (pressure remained almost constant between 742-745 mm of Hg). Although these graphs have been drawn with the same data used in figures 4.55 – 4.72, nonetheless they provide a greater clarity to the explanation made earlier regarding effect of temperature and relative humidity on flashover characteristics for the same ESDD.

It is observed from figures 4.73 – 4.81 that at same ESDD, the flashover voltage is lower for the sample at lower temperature and higher relative humidity. This is due to the reason that at higher relative humidity

the amount of water molecules and hence H^+ and OH^- ions is large. The difference in FOVUID values at low temperature, high relative humidity and high temperature low relative humidity is more significant for highly soluble salts. This may be due to the reason that water is a polar solvent with negative charge on oxygen **[139], [140]** its attraction to cation of univalent salts with smaller charge density (such as K^+ and Na^+) leads to smaller ionic cloud density and therefore more speed of movement. The cations of bivalent salt have larger charge density and therefore the ionic cloud diameter of such ions is larger and therefore has higher FOVUID values.

5.6 Variation of FOVUID on ESDD for different cation and Cl^- anion

Figure 4.82 shows variation of FOVUID with ESDD for the three chlorides, namely NaCl, KCl and $CaCl_2$. It is observed that for the same ESDD the flashover voltage per unit insulation distance is lowest for KCl and highest for $CaCl_2$ with NaCl values being between the two. The reason for difference in the characteristics can be explained on the basis of ionic radii, hydrated radii, degree of hydration, hydration energy, lattice energy, solubility of salts, atomic mass and transportation number.

5.6.1 Effect of ionic and hydrated radii

The conductivity of an ionic solution can be explained on the basis of process of hydration in which the ions get surrounded by water molecules. These hydrated ions move freely in solution and their ability to move explains conductivity of salt species. The extent of hydration depends on the size of the ion. Wherein it has been seen that smaller the size of the ion, more it is hydrated and hence greater is its hydrated radii which results in lesser ionic mobility. It can be seen from figure 4.82 that the drop in FOVUID of KCl is more than NaCl. This is due to the fact that ionic radii of potassium ion (1.38 A°) is greater than sodium ion (0.95 A°), therefore it attracts only a few number of water dipoles (hydrated radii of potassium ion becomes 2.32 A° and that of sodium ion becomes 2.76 A°) resulting in greater ionic mobility of potassium ion than sodium ion owing to smaller

hydrated potassium ion **[115] [140] [141] [142].** The ionic radii of calcium ion (0.99A°) is slightly more than sodium ion, its characteristics curve is above NaCl, although it should be below it. This deviation can be due to the reason that calcium ion is heavier than sodium ion.

5.6.2 Effect of solubility

The difference in the flashover voltage for different salts even for the same ESDD can be well explained by the difference in the solubility of the salts. As already discussed in section 1.2.6 the common occurring salts can be classified on the basis of their solubility in water as solvent. Solubility of a particular salt depends on the lattice energy of the solid and the hydration energy of the ions. As per the Born-Lande equation **[140]** for any anion (in this case Cl^-) the lattice energy decreases as the size of metal increases. The hydration energy also decreases as the metal ions become large. For a substance to dissolve, the hydration energy must exceed the lattice energy. As the metal ions become larger, both the lattice energy and hydration energy decreases. A decrease in lattice energy favours increased solubility, but a decrease in hydration energy favours decreased solubility. These two factors thus change in opposite directions, and the overall effect depends on which of the two has changed the most. With most compounds, as metal gets larger, the hydration energy decreases more rapidly than the lattice energy and hence the compounds become less soluble as the metal gets larger. Based on these factors, the order of solubility for chlorides of sodium, calcium and potassium follows the order $NaCl > CaCl_2 > KCl$**[143].** It can be seen from figure 4.82 the curve for $CaCl_2$ is above NaCl curve due to the order of solubility given above. As per this solubility order, the curve for KCl should be above $CaCl_2$, whereas experimentally it has been obtained to be below NaCl curve. This abnormal behaviour can be understood by considering the transport number of the cations in question.

5.6.3 Effect of cation transportation number

In an electrolytic solution although all ions feel the externally applied electrical field to the extent of their charges, some respond by migrating more than others. Though the burden of carrying the current through the electrolytic solution falls on the whole community of ions, the burden is not shared equally among the various species of ions. Even if there are equal number of the various ions, those which have higher mobility contribute more to the task of transporting current through the electrolytic solution **[144]**.

The transportation number, also called transference number gives the fraction of the total current carried by a given ion in a solution. The transport number of potassium ion (K^+) in solution of KCl at 18 °C is 0.496, whereas that of sodium ion (Na^+) in solution of NaCl at 18 °C is 0.396. Thus the fraction of current carried by K^+ ion is more than Na^+ ion, this suitably explains the reason for more conductivity or ESDD and hence greater drop in FOVUID for KCl in comparison to NaCl. The transportation number of calcium ion (Ca^{2+}) in solution of $CaCl_2$ is 0.424. As per this the FOVUID characteristics should lie between KCl and NaCl, although it lies above NaCl. This again can be due to Ca^{2+} ion being heavier than Na^+ ion (atomic mass of calcium is 40.08 while that of sodium is 22.99). It is worth mentioning that the transport numbers change only slightly with increase in concentration, e.g. transport number of Na^+ ion changes by about 1.7% if normality of solution changes from 0.01 to 0.20 **[141]**. It is worth noting that the transport number is a function of salt solubility and the size of cation **[145]**.

5.7 Variation of FOVUID on ESDD for different cation and SO_4^{2-} anion

Figure 4.83 shows variation of FOVUID with ESDD for the three Sulphate, namely Na_2SO_4, $MgSO_4$ and $CaSO_4$. It is observed that for the same ESDD the flashover voltage per unit insulation distance is lowest for Na_2SO_4 and highest for $CaSO_4$ with values of $MgSO_4$ being between the

two. The reason for difference in the characteristics can be explained on the basis of atomic mass, ionic radii, degree of hydration, solubility of salts and transportation number.

5.7.1 Effect of atomic mass, ionic and hydrated radii

As discussed above the ionic radii of Na^+ ion is 0.95 A° while that of Ca^+ ion is 0.99 A°. Thus the ionic radii and hence the hydrated radii are almost same, therefore for both cation the characteristics curve must have same values. Actually the curve of Na_2SO_4 has lowest value for the same ESDD. This is probably due to lesser atomic mass of sodium (22.99) than calcium (40.08). The atomic mass of magnesium is 24.31, very close to sodium atom and therefore its FOVUID characteristic should lie in between that of sodium and calcium. The ionic radius of magnesium ion is 0.72 A° and therefore its hydrated radii would be biggest as far as the three cation are concerned **[141].** A larger hydrated radius implies that the ionic mobility of magnesium ion would be slowest. Owing to this the FOVUID value for $MgSO_4$ should be highest for the same ESDD in comparison to Na_2SO_4 and $CaSO_4$ whereas it is obtained to be below that of $CaSO_4$. This abnormal characteristic can be explained on the basis of difference in solubility of group II alkaline earth metal i.e. magnesium and calcium

5.7.2 Effect of solubility

The solubility of alkaline earth metal sulphates in water as solvent decreases down the group. Thus solubility of $MgSO_4$ is far more than $CaSO_4$. The significantly higher solubility of $MgSO_4$ than $CaSO_4$ is due to higher enthalpy of solvation of smaller Mg^{2+} ion (0.72 A°) than bigger Ca^{2+} ion (0.99 A°). Thus solubility follows the order $MgSO_4 > CaSO_4$ and hence the characteristic obtained. Combining the explanation given in the previous section solubility follows the order $Na_2SO_4 > MgSO_4 > CaSO_4$ **[140].**

5.7.3 Effect of cation transportation number

The transport number of magnesium ion (Mg^{2+}) in solution of $MgSO_4$ at18 °C is 0.381, whereas that of sodium ion (Na^+) in solution of

Na_2SO_4 at 18 °C is 0.392. Thus the fraction of current carried by Na^+ ion is more than Mg^{2+} ion, this suitably explains the reason for more conductivity or ESDD and hence greater drop in FOVUID for Na_2SO_4 in comparison to $MgSO_4$. The transportation number of calcium ion (Ca^{2+}) in solution of $CaSO_4$ at 18 °C is 0.368, lowest of the three cations and suitably justifying highest values of flashover voltage.

5.8 Variation of FOVUID on ESDD for different cation and NO_3^{2-} anion

Figure 4.84 shows variation of FOVUID with ESDD for the three Nitrates, namely $NaNO_3$, Mg $(NO_3)_2$ and Ca $(NO_3)_2$. It is observed that for the same ESDD the flashover voltage per unit insulation distance is lowest for $NaNO_3$ and highest for Ca $(NO_3)_2$ with Mg $(NO_3)_2$ values being between the two. The reason for difference in the characteristics can be explained on the basis of molecular mass, ionic radii, hydrated radii and solubility.

5.8.1 Effect of molecular mass, ionic and hydrated radii

As already stated the ionic radii of Na^+ ion is 0.95 A° while that of Ca^+ ion is 0.99 A°. Thus the ionic radii and hence the hydrated radii are almost same, therefore for both cation the characteristics curve must have same values. Actually the curve of $NaNO_3$ has lowest value for same ESDD and that of $Ca(NO_3)_2$ has highest value. This is probably due to lesser molecular mass of sodium nitrate (85 amu) than calcium nitrate (164 amu). The molecular mass of magnesium nitrate is 148 amu, and therefore its FOVUID characteristic should lie in between that of sodium nitrate and calcium nitrate. This is what is obtained. The ionic radius of magnesium ion is 0.72 A° and therefore its hydrated radii would be biggest as far as the three cation are concerned. A larger hydrated radius implies that the ionic mobility of magnesium ion would be slowest. Owing to this, the FOVUID value for $Mg(NO_3)_2$ should be highest for the same ESDD in comparison to $NaNO_3$ and $Ca(NO_3)_2$ whereas it is obtained to be below that of $Ca(NO_3)_2$.

This abnormal characteristic can be explained on the basis of difference in solubility of group II alkaline earth metal i.e. magnesium and calcium.

5.8.2 Effect of solubility

The solubility of alkaline earth metal nitrates in water as solvent decreases down the group. Thus solubility of with $Mg(NO_3)_2$ is more than $Ca(NO_3)_2$. The significantly higher solubility of $Mg(NO_3)_2$ than $Ca(NO_3)_2$ is due to higher enthalpy of solvation of smaller Mg^{2+} ion (0.72 A°) than bigger Ca^{2+} ion (0.99 A°). Thus solubility follows the order $Mg(NO_3)_2$> $Ca(NO_3)_2$ and hence the characteristic obtained. Combining the explanation given in the previous section solubility follows the order $NaNO_3$> $Mg(NO_3)_2$ > $Ca(NO_3)_2$ **[140].**

5.9 Variation of FOVUID on ESDD for Na^+, Ca^{2+} and Mg^{2+} and different anion

Figure 4.85 shows the variation of FOVUID with ESDD for sodium cation and three different anions, namely chloride (Cl^-), nitrate (NO_3^-) and Sulphate (SO_4^{2-}). It can be seen that the FOVUID value at same ESDD for the chloride of sodium is the lowest and that the value of the sulphate of sodium is the highest, nitrate of sodium has intermediate values.

Figure 4.86 shows the variation of FOVUID with ESDD for calcium cation and three different anions, namely chloride (Cl^-), nitrate (NO_3^-) and Sulphate (SO_4^{2-}). It can be seen that the FOVUID value at same ESDD for the chloride of calcium is the lowest and that the value of the sulphate of calcium is the highest, nitrate of calcium has intermediate values.

Figure 4.87 shows the variation of FOVUID with ESDD for magnesium cation and two different anions, namely nitrate (NO_3^-) and Sulphate (SO_4^{2-}). It can be seen that the FOVUID value at same ESDD for the nitrate of magnesium is lower and that the value of the sulphate of magnesium is higher.

The reason for getting these characteristics can be explained on the basis of mass of anions and ionic radii of anions.

5.9.1 Effect of molecular mass on mobility of anions

Since the sodium ion is common in the three salts (figure 4.85), the effect of anion mass may be the reason for the variation in characteristics of the three salts. The atomic mass of sulphate ion, nitrate ion and chloride ion is 96, 62 and 35.5 amu respectively. Thus the sulphate ion is heaviest of the three and therefore its mobility is least in comparison to the other anions and therefore the FOVUID values are highest for sodium sulphate. The chloride anion has the least mass of the three and therefore its mobility is highest, thereby resulting in lowest FOVUID values for the same ESDD. The nitrate ion has intermediate mass and therefore intermediate FOVUID values.

For the case with common calcium cation and different anions, the difference in the obtained characteristics can be explained on the basis of anionic mass. As already stated in the previous paragraph, sulphate ion is the heaviest of the three, thereby having least mobility in comparison to chloride that has highest mobility and nitrate having intermediate values of FOVUID.

Similarly for magnesium cation and different anions, the flashover voltage of $MgSO_4$ has highest value in comparison with $MgCl_2$ having lowest values. $Mg(NO_3)_2$ has intermediate values of flashover voltages. The reason for the obtained characteristics being that sulphate ion has highest ionic mass and chloride ion has the least mass, nitrate ion has intermediate ionic mass.

The characteristic obtained (figures 4.85, 4.86, 4.87) is similar to that reported by Williams et al **[18]** for a flat plate insulator. Although they reported that only cationic mass was responsible for the obtained characteristics, whereas in this report, effect of anionic mass has also been suggested as the reason for the characteristics obtained.

5.9.2 Effect of ionic radii of anions

It has already been explained that the ionic radii of cations play a vital role as far as movement of cations is concerned. The ionic radii of anions also affect their movement. The ionic radii of chloride ion (Cl^-) is 1.81 A°,

nitrate ion (NO_3^-) has ionic radii of 1.89 A° and sulphate (SO_4^{2-}) ion has ionic radii of 2.30 A° The polar water molecule has two positive charges on hydrogen. The anions attract these positive charges and swell in size, thus reducing their speed of movement **[146][147][148] [140].**

The increase in ionic size i.e. the hydrated ion size of sulphate ion is more as compared to chloride and nitrate ions. Thus in figures 4.85, 4.86 and 4.87, the chlorides have lowest FOVUID for same ESDD and sulphate has highest FOVUID values. Since the hydrated radius of nitrate ions is between the chloride and sulphate ion, the FOVUID values are between the two for the same ESDD. The obtained pattern is similar to what has been reported earlier **[18] [75].**

5.10 Variation of WSVUID, FOVUID on pH

Figures 4.94 – 4.111 gives variation of WSVUID and FOVUID with pH at different temperature, pressure and relative humidity. It is observed that the pH of the single salts used varied between 7.2 and 7.8. For all the salts it is observed that increase in pH leads to corresponding decrease in FOVUID. This fall may be attributed to the fact that as the pH increases above 7, the number of hydroxyl ion (OH^-) increases, that is, the electrolytic solution becoming more basic resulting in increased conductivity and corresponding decrease in value at which flashover occurs.

5.11 Variation of FOVUID on pH at different ambient conditions

Figures 4.112 – 4.120 gives variation of FOVUID with pH for all the single salts at different temperature and relative humidity (pressure remaining almost constant in the range 742-745 mm of Hg). The reason for taking only the flashover characteristics has been explained in the preceding section. It is observed that at higher relative humidity the water (moisture) content is higher and therefore additional hydrogen ions (H^+) and hydroxyl ions (OH^-) are available. This increase in the total number of ions at higher relative humidity implies that for the same pH the sample tested at higher relative humidity flashovers at lower voltage owing to increase in

conductivity . On critical examination of the graphs 4.112 – 4.120 it is clear that more the difference in the relative humidity for a particular salt, more pronounced is the difference between the two trend lines of a particular graph. This difference is more visible for salts having higher solubility such as NaCl, KCl, $NaNO_3$ and Mg $(NO_3)_2$, owing to ease of flow of the corresponding ions on wetting.

5.12 Variation of FOVUID on pH for different cation and Cl^-, SO_4^{2-}, NO_3^{2-} anion

Figure 4.121 shows variation of FOVUID with pH for the three chlorides (NaCl, KCl and $CaCl_2$) under study. It is observed that FOVUID value of NaCl fall by about 13% for 0.12 decrease in pH(Corresponding increase in [H^+] is 31%), for KCl value fall by about 29% for 0.17 decrease in pH(Corresponding increase in [H^+] is 47%), $CaCl_2$ value fall by about 17% for 0.14 decrease in pH (increase in [H^+] is 38%). This difference in characteristics may be due to the different chemical nature of hydroxides and acids (HCl) that are formed on reaction of these chlorides with water.

Figure 4.122 shows variation of FOVUID with pH for the three sulphates (Na_2SO_4, MgSO4 and $CaSO_4$) under study. It is observed that FOVUID value of Na_2SO_4 fall by about 20% for 0.15 decrease in pH(Corresponding increase in [H^+] is 41%), for $MgSO_4$ value fall by about 23% for 0.17 decrease in pH(Corresponding increase in [H^+] is 41%), $CaSO_4$ value fall by about 12% for 0.05 decrease in pH (12% increase in [H^+] is 38%). This difference in characteristics may be due to the different chemical nature of hydroxides and acids (H_2SO_4) that are formed on reaction of these sulphates with water.

Figure 4.123 shows variation of FOVUID with pH for the three nitrates ($NaNO_3$, $Ca(NO_3)_2$ and $Mg(NO_3)_2$) under study. It is observed that FOVUID value of $NaNO_3$ fall by about 20% for 0.15 decrease in pH(Corresponding increase in [H^+] is 41%), for $Ca(NO_3)_2$ value fall by about 15% for 0.14 decrease in pH(Corresponding increase in [H^+] is 38%),

$Mg(NO_3)_2$ value fall by about 20% for 0.10 decrease in pH (25% increase in [H^+] is 38%). This difference in characteristics may be due to the different chemical nature of hydroxides and acids (HNO_3) that are formed on reaction of these nitrates with water.

A more critical examination follows in section 5.13

5.13 Variation of FOVUID on pH for Na^+, Ca^{2+} and Mg^{2+} and different anion

Figure 4.124 shows variation of a common cation and different anion. It is observed that lower FOVUID values are obtained for NaCl and highest for Na_2SO_4. Since the hydroxide formed (sodium hydroxide) is same for all three, this may be due to the reason of difference in characteristics of the acids i.e. hydrochloric acid, sulphuric acid and nitric acid.

Figure 4.125 shows variation of a common cation and different anion. It is observed that lower FOVUID values are obtained for $CaCl_2$ and highest for $CaSO_4$. Since the hydroxide formed (calcium hydroxide) is same for all three, this may be due to the reason of difference in characteristics of the acids i.e. hydrochloric acid, sulphuric acid and nitric acid.

Figure 4.126 shows variation of a common cation and different anion. It is observed that lower FOVUID values are obtained for $Mg(NO_3)_2$ and higher for $MgSO_4$. Since the hydroxide formed (magnesium hydroxide) is same for both cases, this may be due to the reason of difference in characteristics of the acids i.e. sulphuric acid and nitric acid.

Double Salts as Contaminant

To understand the effect of different ion species on flashover performance of insulators few double salt slurries were also used as contaminants. NaCl + $CaSO_4$, KCl + $CaSO_4$, NaCl + CaO, KCl + CaO, $CaSO_4$ + CaO and $Mg(NO_3)_2$ + CaO have been used as contaminant. This section deals with the analysis of the obtained results for multi salt contaminant. The effect of single salt contaminant and double salt

contaminant on the insulation characteristics with respect to FOVUID is given below.

5.14 Variation of FOVUID on ESDD due to addition of Calcium Sulphate to Sodium Chloride and Potassium Chloride

Figure 4.88 shows comparison of FOVUID with ESDD for single NaCl contaminated insulator, single $CaSO_4$ and NaCl+ $CaSO_4$ contaminated insulator. It is observed that for the same ESDD the FOVUID values for only NaCl contaminated insulator are lowest and that of only $CaSO_4$ contaminated insulator are highest. The insulator contaminated with slurry containing both NaCl and $CaSO_4$ has intermediate values of FOVUID for same ESDD.

Figure 4.89 shows comparison of FOVUID with ESDD for single KCl contaminated insulator, single $CaSO_4$ and KCl+ $CaSO_4$ contaminated insulator. It is observed that for same ESDD the FOVUID values for only KCl contaminated insulator are lowest and that of only $CaSO_4$ contaminated insulator are highest. The insulator contaminated with slurry containing both KCl and $CaSO_4$ has intermediate values of FOVUID for same ESDD.

The reason for the obtained characteristics can be explained on the basis of extent of solubility in water and activity coefficient of ions.

5.14.1 Effect of Solubility in water

Table 1.3 classifies salts on the basis of solubility. Salts such as NaCl, KCl are highly soluble with solubility of more than 3 grams/liter while $CaSO_4$ is a lowly soluble salt with solubility less than 2 grams/liter. Owing to this difference in the solubility, the electrolytic solution of NaCl and KCl has greater dissociation of ions, therefore greater mobility and hence more leakage current flows on insulator surface leading to lower flashover voltage. For a pure $CaSO_4$ solution the dissociation of ions is not much and therefore lesser mobility of ions, lesser leakage current and higher flashover voltage.

For NaCl+ $CaSO_4$ and KCl+ $CaSO_4$ the mobility of Na^+ and K^+ is impeded in comparison to their movement in solution of only NaCl and KCl. Thus the values of leakage current is less and hence higher FOVUID values.

5.14.2 Effect of Activity coefficient of ions

If a highly soluble salt is added to a lowly soluble salt, it is observed that solubility of the lowly soluble salt increases. This is due to the reason that additional ions are formed leading to marked decrease in the mean activity coefficient of ions. Decrease in mean activity coefficient leads to increased solubility as solubility is inversely proportional to the mean activity coefficient **[150][151].** Thus the FOVUID characteristic of NaCl+ $CaSO_4$ and KCl+ $CaSO_4$ is below the $CaSO_4$ characteristic.

5.15 Variation of FOVUID on ESDD due to addition of Calcium Oxide to Sodium Chloride, Potassium Chloride, Calcium Sulphate and Magnesium Nitrate

Figures 4.90 – 4.93 shows variation of FOVUID with ESDD due to addition of insoluble calcium oxide (CaO) to NaCl, KCl, $CaSO_4$ and $Mg(NO_3)_2$. It is observed that the characteristic of CaO added contaminant is above the characteristic of the single soluble salts. The reason for the difference in the obtained characteristic can be explained on the basis of insoluble nature of CaO.

5.15.1 Effect of insoluble Calcium Oxide

Calcium oxide is sparingly soluble (almost insoluble) in water as solvent. Therefore when it is mixed with soluble salts it forms an inert matrix and impedes the flow of ions resulting in lesser leakage current and thereby higher flashover voltage in comparison to single salt.

The difference in FOVUID values is more pronounced for highly soluble salts, as can be seen from graphs 4.90 and 4.91. Whereas when lowly soluble salt such as $CaSO_4$ and Mg $(NO_3)_2$ are mixed with CaO the change in FOVUID is not significant. This is because the lowly soluble salts have lesser dissociation of ions.

5.16 Variation of FOVUID on pH due to addition of lowly soluble salt to Sodium Chloride, Potassium Chloride and Magnesium Nitrate

Figures 4.127 – 4.132 shows variation of FOVUID for single and double salts. The difference in characteristics due to the nature of different hydroxides and the acids formed (section 5.13)

5.17 Variation of FOVUID on percentage of highly soluble and lowly soluble components

The bar charts given in figures 4.133 – 4.138 shows that as the percentage (by weight) of lowly soluble or insoluble salt increases in a mixture of highly soluble salt the FOVUID increases. This is due to the reason that as the percentage of more dissociating salt decreases, the number of ions liberated in the electrolytic solution decreases resulting in lesser mobility of ions and hence lesser flow of leakage current and higher flashover voltage. It is observed that for KCl and NaCl percent increase in FOVUID is more when quantity of sparingly soluble or insoluble salt is increased and that of highly soluble NaCl and KCl is decreased. This is due to the reason that as quantity of salts with higher degree of dissociation (such as NaCl, KCl) is decreased, the number of ions decreases and thereby less leakage current and hence higher flashover voltage. The drop of FOVUID is comparatively less when quantity of CaO is increased. Increase of CaO leads to formation of inert matrix that should lead to higher flashover voltage due to impeding ionic movement but it is observed that there is significant drop in flashover voltage. This may be attributed to a greater water holding capacity of the resulting mixture of CaO and soluble salts [17].

Section C: DISCUSSION ON PROPOSED MODEL

5.18 Proposed model for determination of FOVUID

Based on extensive experimentation with natural and artificial pollutants on porcelain disc insulators a model that relates FOVUID with ESDD is proposed for different areas. Since the artificial pollution tests were

carried out using variety of soluble salts, these salts representing their occurrence in different geographical regions. If we consider case of Aligarh (site of present study) and its geographical location, it is clear that traces of chlorides of sodium, potassium and magnesium would be low as the nearest sea coast is almost 1000 km away. For this inland location the salts that are found predominantly are $CaSO_4$ and $MgSO_4$. In addition to this SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, P_2O_5 ,cations of heavy metals such as Cu, Zn, Fe, Pb and anions Cl^-, SO_4^{2-}, PO_4^{3-} CO_3^{2-} are also found due to presence of sources producing them.

It is proposed that the following model be used for finding flashover voltage per unit insulation distance for insulators installed at Aligarh or any other inland area far away from seacoast. This model has been arrived at by considering the experimental data with various soluble salts and CaO.

$$FOVUID = A(ESDD)^{-B}$$

$$FOV = AL(ESDD)^{-B}$$

Where,

FOVUID = Flashover voltage per insulation distance (kV/cm)

FOV = Flashover voltage (kV)

A, B are constants , the values are-

A= 1.15

B = 0.3

L = Unit leakage distance (cm)

Values of A and B need to be evaluated for different climatic conditions. The above values are applicable to arid and semi-arid regions.

5.18.1 Application of the model for finding FOVUID for insulators installed at Aligarh

In table 5.1, the values obtained from experiments (as given in tables 4.1 - 4.18) and values obtained from the model (section 5.18) are tabulated for location 1. Table 5.2 gives the comparative values for location 2 and table 5.3 gives the values for location 3.

The difference in experimental values and calculated or predicted values is within ± 6% for most of the readings. However, there are some

values that fall within ± 10%. The difference is higher (around ± 14%) for location 2. The reasons for difference in the experimental and observed values can be due to some of the following reasons.

1. The model has been arrived at after experiments with number of soluble salts and only one insoluble salt (CaO), whereas under natural conditions variety of non soluble components would be present.
2. The experimental values of natural test have been obtained for a range of temperature and relative humidity whereas in artificial test with various salts the value of temperature and RH differed. Moreover, the pressure was almost constant.
3. The difference is large for location 2 (thermal plant) because of the chemical effects of fly ash, SO_X, NO_X etc. For arriving at the model effect of fly ash has not been considered.
4. The differences are somewhat higher for March 2008 samples. The proposed model did not take into account such unusual fog condition. Nonetheless, the model predicts FOVUID values for such unusual weather conditions within ± 12% of the experimental values.

It is of interest to note from figure 5.1 that the proposed model gives lower average values of FOVUID in most of the cases. Thus it is opined that using the model shall lead to a safer design.

Considering the above, it is suggested that the proposed model can be used for predicting flashover voltage (FOV) for semi-arid/ sub-tropical climatic zones similar to Aligarh.

Table 5.1 Comparison of experimental values of FOVUID and value obtained from proposed model for NH-91 (Location 1)

S.No	ESDD (mg/cm^2)	Experimental Values FOVUID (kV/cm)	Model Values FOVUID (kV/cm)	Difference in model values (%)
1	0.0422	3.114	2.972	-4.5
2	0.0435	3.081	2.945	-4.4
3	0.0445	3.032	2.906	-4.2
4	0.0460	3.000	2.896	-3.4
5	0.0467	2.967	2.883	-2.8
6	0.0476	2.950	2.866	-2.8
7	0.0482	2.918	2.856	-2.1
8	0.0486	2.885	2.849	-2
9	0.0407	3.229	3.004	-6.9
10	0.0417	3.196	2.983	-6.6
11	0.0427	3.163	2.961	-6.3
12	0.0433	3.114	2.949	-5.3
13	0.0445	3.081	2.925	-5.1
14	0.0457	3.049	2.902	-4.8
15	0.0468	3.032	2.881	-5.0
16	0.0474	3.000	2.870	-4.3
17	0.0389	3.065	3.045	-0.6
18	0.0402	3.032	3.015	-1.6
19	0.0409	3.000	3.000	0
20	0.0420	2.983	2.976	-0.2
21	0.0431	2.950	2.953	+0.1
22	0.0444	2.934	2.927	-0.2
23	0.0462	2.918	2.892	-0.8
24	0.0477	2.885	2.865	-0.7
25	0.0304	3.114	3.279	+5.3
26	0.0317	3.081	3.238	+5.1
27	0.0328	3.049	3.205	+5.1
28	0.0338	3.016	3.177	+5.3

S.No	ESDD (mg/cm^2)	Experimental Values FOVUID (kV/cm)	Model Values FOVUID (kV/cm)	Difference in model values (%)
29	0.0351	3.000	3.141	+4.7
30	0.0357	2.983	3.125	+4.7
31	0.0366	2.950	3.102	+5.1
32	0.0372	2.934	3.086	+5.2
33	0.0374	3.114	3.082	-1.0
34	0.0384	3.081	3.057	-0.75
35	0.0392	3.032	3.038	+0.2
36	0.0400	3.016	3.020	+0.1
37	0.0407	3.000	3.004	+0.1
38	0.0418	2.967	2.980	+0.4
39	0.0431	2.950	2.980	+1
40	0.0447	2.934	2.953	+0.6
41	0.0474	2.786	2.870	+3.0
42	0.0492	2.754	2.838	+3.0
43	0.0496	2.721	2.831	+4.0
44	0.0504	2.672	2.818	+5.46
45	0.0510	2.622	2.808	+7.1
46	0.0519	2.573	2.793	+8.5
47	0.0532	2.540	2.772	+9.1
48	0.0546	2.508	2.751	+9.7

Table 5.2 Comparison of experimental values of FOVUID and value obtained from proposed model for Thermal Plant (Location 2)

S.No	ESDD (mg/cm^2)	Experimental Values FOVUID (kV/cm)	Model Values FOVUID (kV/cm)	Difference in model values (%)
1	0.0532	3.065	2.772	-9.5
2	0.0551	3.032	2.743	-9.5
3	0.0562	3.000	2.727	-9.0
4	0.0573	2.967	2.711	-8.6
5	0.0583	2.934	2.697	-8.0
6	0.0594	2.901	2.682	-7.5
7	0.0605	2.868	2.667	-6.9
8	0.0620	2.836	2.648	-6.6
9	0.0575	3.147	2.708	-13.9
10	0.0588	3.114	2.690	-13.5
11	0.0599	3.081	2.675	-13.1
12	0.0604	3.049	2.669	-12.4
13	0.0615	3.016	2.654	-12.0
14	0.0620	3.000	2.648	-11.7
15	0.0628	2.967	2.638	-11.1
16	0.0642	2.934	2.620	-10.6
17	0.0502	3.065	2.821	-7.9
18	0.0524	3.032	2.785	-8.1
19	0.0530	3.000	2.775	-7.5
20	0.0546	2.967	2.751	-7.2
21	0.0563	2.934	2.726	-7.1
22	0.0583	2.901	2.697	-7.0
23	0.0593	2.868	2.683	-6.4
24	0.0614	2.836	2.656	-6.3
25	0.0436	3.213	2.943	-8.3
26	0.0453	3.196	2.909	-8.9
27	0.0460	3.180	2.896	-8.9
28	0.0462	3.147	2.892	-8.1

S.No	ESDD (mg/cm^2)	Experimental Values FOVUID (kV/cm)	Model Values FOVUID (kV/cm)	Difference in model values (%)
29	0.0474	3.131	2.870	- 8.3
30	0.0487	3.098	2.847	- 8.1
31	0.0498	3.065	2.828	- 7.7
32	0.0514	3.032	2.801	- 7.5
33	0.0564	2.901	2.724	- 6.0
34	0.0572	2.868	2.713	- 5.4
35	0.0584	2.836	2.696	- 4.9
36	0.0594	2.803	2.682	- 4.3
37	0.0602	2.770	2.671	- 3.5
38	0.0615	2.737	2.654	- 3.0
39	0.0629	2.721	2.636	- 3.0
40	0.0635	2.721	2.629	-3.3
41	0.0532	2.639	2.772	+5.0
42	0.0544	2.622	2.754	+5.0
43	0.0551	2.573	2.743	+6.6
44	0.0560	2.524	2.730	+8.1
45	0.0576	2.475	2.707	+9.3
46	0.0581	2.442	2.700	+10.5
47	0.0592	2.409	2.685	+11.5
48	0.0601	2.377	2.673	+12.5

Table 5.3 Comparison of experimental values of FOVUID and value obtained from proposed model for Nishat Apartment (Location 3)

S.No	ESDD (mg/cm^2)	Experimental Values FOVUID (kV/cm)	Model Values FOVUID (kV/cm)	Difference in model values (%)
1	0.0338	3.245	3.117	-2.0
2	0.0344	3.213	3.160	-1.6
3	0.0357	3.180	3.125	-1.7
4	0.0367	3.147	3.099	-1.5
5	0.0376	3.131	3.077	-1.7
6	0.0373	3.131	3.085	-1.5
7	0.0382	3.098	3.063	-1.1
8	0.0395	3.081	3.032	-1.6
9	0.0347	3.262	3.152	-2.4
10	0.0355	3.229	3.130	-3.0
11	0.0363	3.213	3.109	-3.2
12	0.0367	3.196	3.099	-3.0
13	0.0371	3.180	3.089	-2.8
14	0.0376	3.180	3.077	-3.2
15	0.0387	3.163	3.051	-3.5
16	0.0393	3.163	3.037	-4.0
17	0.0332	3.213	3.194	-0.6
18	0.0336	3.180	3.183	+0.1
19	0.0345	3.147	3.157	+0.3
20	0.0350	3.131	3.143	+0.4
21	0.0355	3.114	3.130	+0.5
22	0.0358	3.098	3.122	+0.8
23	0.0368	3.081	3.097	+0.5
24	0.0373	3.081	3.084	+0.1
25	0.0261	3.278	3.433	+4.7
26	0.0267	3.245	3.410	+5.1
27	0.0281	3.213	3.358	+4.5
28	0.0290	3.18	3.326	+4.6

S.No	ESDD (mg/cm^2)	Experimental Values FOVUID (kV/cm)	Model Values FOVUID (kV/cm)	Difference in model values (%)
29	0.0305	3.163	3.276	+3.6
30	0.0308	3.147	3.267	+3.8
31	0.0312	3.131	3.254	+3.9
32	0.0317	3.114	3.238	+4.0
33	0.0286	3.213	3.340	+4.0
34	0.0299	3.180	3.296	+3.6
35	0.0311	3.147	3.257	+3.5
36	0.0324	3.131	3.218	+2.8
37	0.0339	3.081	3.174	+3.0
38	0.0353	3.065	3.135	+1.3
39	0.0364	3.065	3.107	+1.3
40	0.0364	3.049	3.107	+1.9
41	0.0346	3.081	3.154	+2.3
42	0.0360	3.032	3.117	+2.8
43	0.0368	3.016	3.097	+2.7
44	0.0378	3.000	3.072	+2.4
45	0.0384	2.983	3.057	+2.5
46	0.0395	2.95	3.031	+2.8
47	0.0413	2.934	2.992	+2.0
48	0.0422	2.918	2.972	+1.8

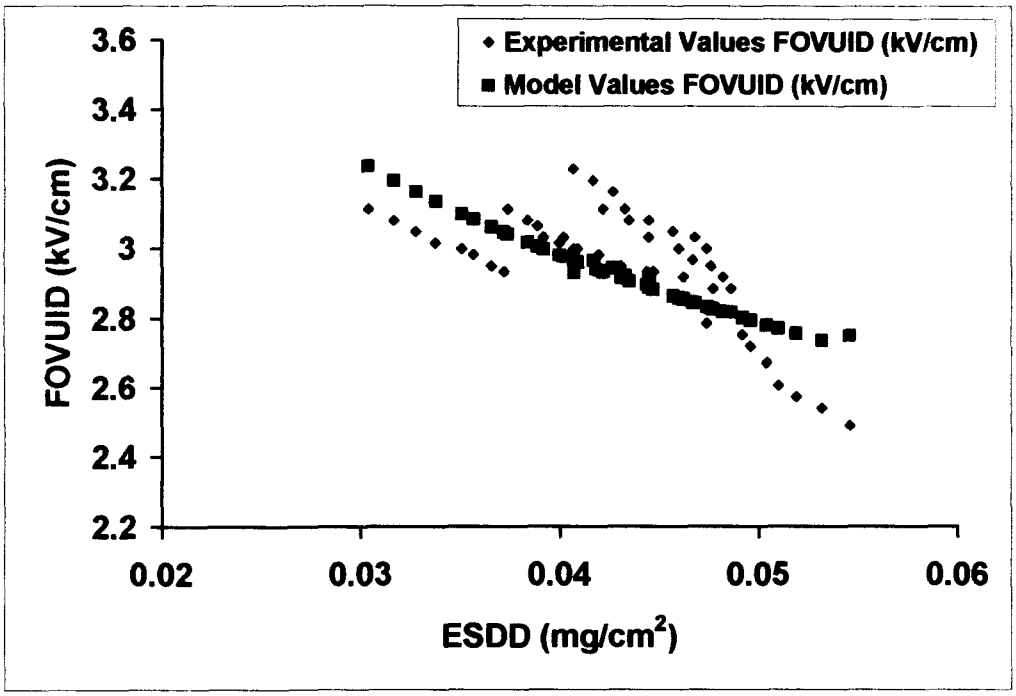


Fig. 5.1 Comparative Graph of Experimental and Model Values

Chapter-6

Summary & Conclusion

6.1 Summary and Conclusions

Having regard to the increasing transmission voltages, reliability and integrity of overhead line insulators is of prime concern. The insulators used in overhead electrical power transmission networks are susceptible to contamination induced flashover due to interaction of atmospheric moisture with the contaminants. These flashovers lead to line outages, resulting in large scale economic loss. Judicious and economical design can be obtained only if proper tests under natural conditions are done. Although tests under natural conditions (i.e. both pollutant and wetting being natural) would seem more realistic, they are subject to large errors, scatter and require large time. Artificial or simulated test methods (i.e. both pollutant and wetting being artificial) have been used since last 60 years. In this thesis results from tests under natural conditions have been reported for a period of 30 months at Aligarh (India). A semi natural method of testing has been proposed wherein different salts were used as pollutant and wetting was natural (by exposure of contaminated insulator to natural fog/wetting). Results of these tests were used for arriving at a model that can be used for predicting FOV for insulators installed in and around Aligarh and also for those regions having similar geographical, environmental conditions.

Continuous monitoring of line insulators should be done to assess the health of insulators. Utilities around the world have been using number of methods to assess the condition of the insulating material. For a fair and effective assessment, the severity of pollution at a particular site should be known accurately. The known methods reported **[17]** for measuring site severity is –

(i) conductivity measurement by removing contaminant i.e. ESDD measurement
(ii) conductivity measurement without removing contaminant
(iii) chemical analysis or cation/ anion analysis
(iv) leakage current measurement
(v) use of directional dust deposit gauge

Since each site has a specific need as for as insulation requirement is concerned, due to difference in the level of pollution, this thesis suggests after extensive experimentation, a new additional severity indicator recognized as pH of the contaminant. Since change of pH implies change in the number of hydrogen and hydroxyl ion, this change leads to overall change in number of ions available for migration. Thus electrical activity due to change in pH is bound to affect the current flow. This chemical property of deposit may provide a deeper insight into the behaviour of the chemicals acting as contaminant on insulators.

The conclusion drawn, based on discussion as given in chapter 5 after experimentation under natural pollutant – natural wetting conditions are:

i. The qualitative chemical analysis of dust content leads to the knowledge of cations/anions present in Aligarh. The ions are Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, CO_3^{2-}, Cl^-, NO_3^{2-} and SO_4^{2-}.

ii. These ions are present due to hydrogeological reasons. The surface and ground water contains these ions, so discharge of this water leads to dispersion of these ions in environment.

iii. The industrial activity in and around Aligarh also contributes to the characteristics obtained at various sites.

iv. Metal processing industry leads to presence of Cd, Cr, Pb, Fe, Cu, Ni, Zn, Mn in soil and ground water and due to erosion and dispersion, may affect electrical behaviour of insulators.

v. Fly ash, particulates from vehicular emission, conductive components of fertilizers also affect the withstand and flashover characteristics.

vi. The insoluble components, although does not make direct contribution to conductivity, nonetheless it affects the withstand and flashover characteristics, owing to water holding capacity and formation of inert matrix that impedes movement of ions.

vii. pH of the solvent i.e. water also affects the withstand and flashover characteristics. If the obtained results are interpolated, acid rains (pH ~ 5.6) may lower FOVUID and WSVUID values.

viii. Higher relative humidity also has a significant effect on withstand and flashover characteristics.

The conclusion drawn, based on discussion as given in chapter 5 after experimentation under artificial pollutant – natural wetting conditions are:

i. Temperature and relative humidity have significant effect on withstand and flashover characteristics (Atmospheric pressure practically remaining constant in the range 742-745 mm of Hg).

ii. At higher relative humidity more dissociated water molecules are available to transport current and hence lower withstand and flashover voltage results.

iii. Polar characteristics of water molecule lead to its attraction to univalent cation (Na^+, K^+), causing smaller ionic cloud density and more speed of movement. This attraction is small for large charge density bivalent cations (Ca^{2+}, Mg^{2+}).

iv. The difference in ionic and hydrated radii of ions affects the mobility and hence the withstand and flashover characteristics.

v. Solubility of salt also plays major role in deciding the withstand and flashover characteristics.

vi. In an electrolytic solution, the burden of carrying current is not shared equally by all ions. Thus transportation number or transference number of ions affects the current flow.

vii. Atomic and molecular mass of the deposited salts also decides the insulating capability of an insulator.

viii. pH of the deposit, in addition to solvent affects withstand and flashover characteristics.

ix. Aqueous solution of deposits has different pH because after interaction with water, the dissociated ions may combine to form acids. Thus pH can be suitably taken as pollution severity indicator.

x. For multi salt contamination, the interaction of multi cations, anions govern the behaviour of the insulator under pollution.

xi. Sparingly soluble, insoluble salts are not contributors to conductivity but affect withstand and flashover characteristics due to water hold capacity and inert matrix formation.

xii. Activity coefficient of ions is also responsible for drop in withstand and flashover characteristics of sparingly soluble, insoluble salt after a highly soluble salt is added to it.

xiii. The proposed model obtained after detailed experimentation with various soluble and non-soluble salt can be used for predicting the flashover voltages for naturally installed insulators.

xiv. The model was used to find values of FOVUID for insulators installed in and around Aligarh. The values obtained with the model were in close agreement with the experimental values.

6.2 Research Contribution

The work that has been reported in this thesis is intended to give an insight into the behaviour of insulators under varied pollution conditions. For proper understanding it was necessary that tests under both natural and artificial pollution conditions are conducted. The author feels that after completing the work that spanned almost 3 years and after detailed analysis of the chemical phenomena that determined the insulating capability of

insulators, following research contributions have been made vis-à-vis porcelain disc insulators

i. A first study reported for insulators installed in and around Aligarh (UP, India).

ii. The study period was around 30 months. Thus the study period has subjected the insulators with almost all climatic cycles in and around Aligarh.

iii. A pollution mapping of the area surrounding Aligarh has been arrived at by estimating pollution level of three representative locations.

iv. A semi-natural method of testing insulators has been proposed. In the reported method, the pollutants were artificial whereas the wetting achieved was natural (fog).

v. This method is very economical as no additional equipments for creation of artificial wetting conditions are required.

vi. Almost all the soluble salts that are dispersed in and around Aligarh have been taken as pollutants for the semi-natural tests.

vii. Detailed chemical analysis of the pollutants has been given.

viii. In the present work, pH has also been suggested as a new indicator of pollution severity. This indicator may be used in addition to existing indicators such as ESDD, leakage current for devising proper maintenance schedule.

ix. The pH of the contaminant can be used for continuous monitoring of overhead line insulators. It is suggested that hot line washing should only be started the after pH of the contaminant deposit exceeds the predetermined value.

Often hot line washing may be started even though it is not required, may be keeping factor of safety in mind. This is quite costly, as can be seen from the cost incurred in hot line washing using helicopters in the northern grid of India (Appendix A-7). Thus it is suggested that

contaminant pH may be taken as an indicator for starting maintenance procedure.

x. The effect of ionic radii, hydrated radii has been established on FOVUID values

xi. The hydration energy and lattice energy of salts has a pronounced effect on flashover characteristics.

xii. The solubility of salts plays a major role in deciding FOVUID values.

xiii. The transportation number of ions decides the percentage of current carried by a particular ion and therefore affects flashover characteristics.

xiv. The atomic mass and molecular mass of salts decides the FOVUID values.

xv. The activity coefficient of ions has been identified as the reasons for the different behavior of a particular pollutant vis-à-vis flashover performance of porcelain insulators.

xvi. A model has been proposed that can be used for predicting flashover voltage for insulators installed in semi-arid/subtropical climatic zone, similar to Aligarh.

6.3 Future Work

Although the author has tried to simulate conditions similar to that prevailing in and around Aligarh artificially, nonetheless it is suggested that future studies must consider the following.

i. The test samples should be installed at the representative locations under energized state for a more fair assessment of insulator performance.

ii. A more detailed weather data should be collected for a clearer picture of insulator performance.

iii. Apart from CaO, other non soluble salts must be used alongwith soluble salts.

iv. The author suggests that various agricultural fertilizers, fly ash should also be used with non-soluble and soluble salts for a good idea of insulator performance. This is necessary because the overhead lines mostly pass through agricultural fields and naturally the components of fertilizers would affect flashover performance.

v. It is suggested that biological contaminants should also be considered alongwith the used salts to model conditions of tropical rain forest areas.

vi. Since pH of contaminants has been suggested as a new pollution severity indicator, future studies should be done to develop remote pH monitors (PHM) similar to leakage current monitors (LCM).

vii. The development of PHM should be utilized for devising proper maintenance schedule.

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Appendix

APPENDIX A-1

For ESDD Calculations

Salt deposit density (SDD) has been identified as a method of assessing degree of pollution. In this method weight of pollutant deposited on the insulator is divided by the surface area of insulator, this method is unsuitable as a measure of pollution because there is no definite correspondence between the weight of pollution and flashover performance **[25].**

Equivalent salt deposit density (ESDD) is being used as a suitable method for assessing degree of pollution. The actual reason that leads insulator to flashover under pollution is because of the electrolytes of wetted pollutants cause a reduction in the layer resistivity of insulator surface. Figure 1 shows that Flashover voltage obtained by NaCl gives minimum values **[25]**. Therefore, it can be inferred that the evaluation of insulator performance by using NaCl equivalent is safe.

ESDD measurement involves removing the contaminants from the insulator surface, thoroughly mixing them in water and measuring the conductivity imparted by the contaminants. For porcelain and glass materials, which are inert and easily wettable, this is a meaningful method for assessing the contamination severity **[102].** ESDD is obtained by measuring conductivities of pollutants and indicated in equivalent amounts of NaCl having equivalent conductivities **[122]**

Rag Wipe Technique:

The ESDD of an unknown deposit is measured by washing all the contaminant from a known area on the insulator surface into a known volume of distilled water. The expression for ESDD can be derived by definition and simple dimensional analysis **[97]**

$$ESDD = \frac{\sigma V}{\sigma_{eq} A} \qquad (1)$$

Since the equivalent conductance of NaCl is not constant but depends on concentration and the temperature corrections applied differ for different ions, there are certain errors which creep into ESDD calculation from eq.(1) above.

Chisholm et al **[97]** suggested the following equation for calculation of ESDD

$$ESDD = \frac{0.42V}{A}\left[\frac{\sigma}{1+C_t(T_w - 20^0C)}\right]^{1.039} \qquad (2)$$

Where:

V is the wash water volume in Litre

A is the area of the contaminated surface in m^2

σ is the wash water conductivity at T_W in μS

T_W is the wash water temperature in ^0C

C_t is the temperature coefficient ($0.02/^0C$)

ESDD is in units of mg/m^2

Sample Calculation:

For sample 1 (Table 4.1)

V = 1 Litre

A = 1599 x 10^{-4} m^2

σ = 129.05 μS

$T_W = 18.6^0C$

Putting these values in equation (2) given above

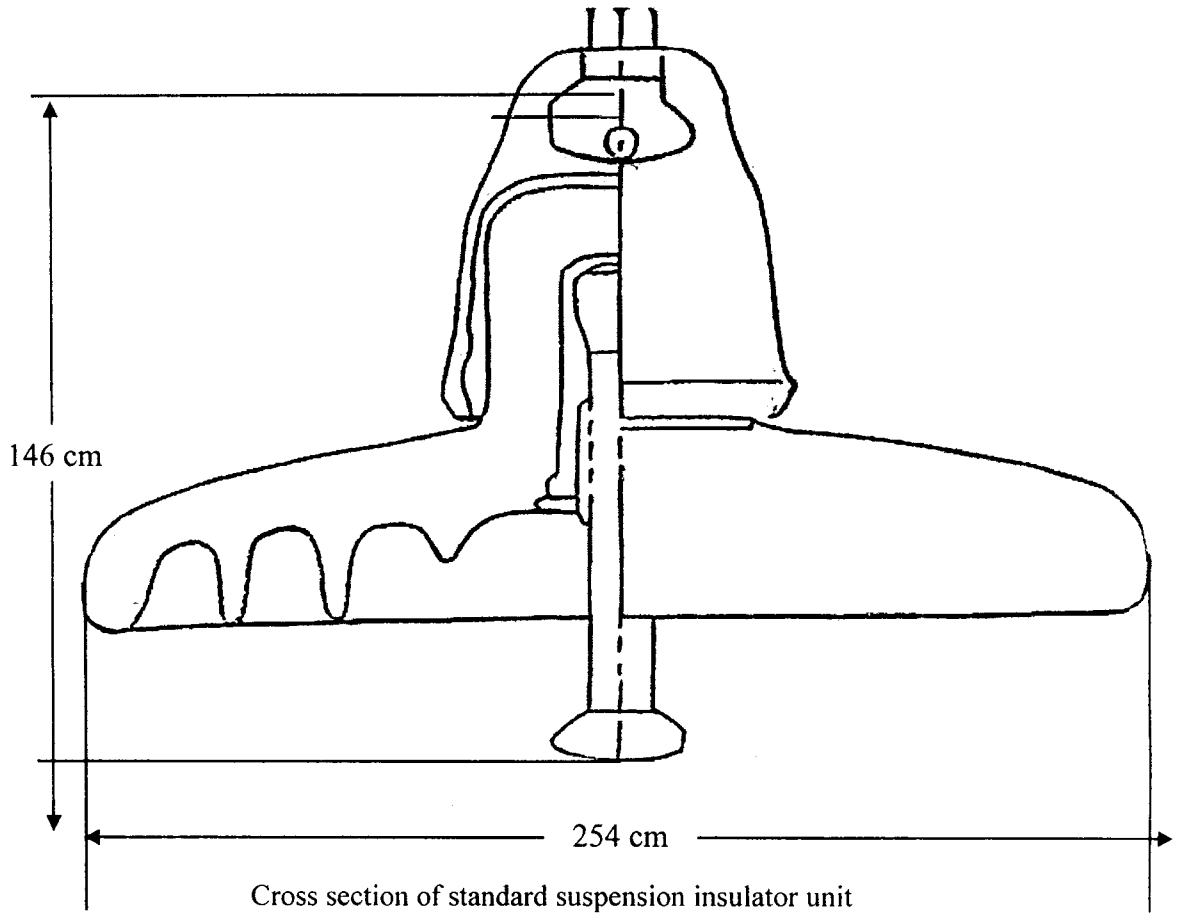
$$ESDD = \frac{0.42x1}{1599x10^{-4}}\left[\frac{129.05}{1+.02(18.6-20)}\right]^{1.039}$$

$= 421.98\ mg/m^2$

$= 0.0422\ mg/cm^2$

APPENDIX A-2

The insulator surface area was calculated using the method as given **[118], [25]**



Cross section of standard suspension insulator unit

Shed Diameter: 254 cm
Unit Spacing: 146 cm
Leakage Distance: 305 cm
Top Surface Area: 691cm^2
Bottom Surface Area: 908 cm^2
Total Surface Area: 1599 cm^2

Figure A.1: Dimensions of Cap and Pin type insulator used

APPENDIX A-3

Calibration curve for Testing Transformer

The high voltage was obtained from a testing transformer of 150 kV, 50 Hz, 1-phase, 30 kVA rating. The short circuit current of the testing transformer was 15 A at maximum excitation. The voltages were measured using a voltmeter (accuracy ± **3%**) connected to the primary side of the transformer, that reads the low side voltage. The corresponding high voltages are obtained from a calibration curve drawn by using the sphere – sphere electrode system having diameter of 25 cm **[117] [118].**

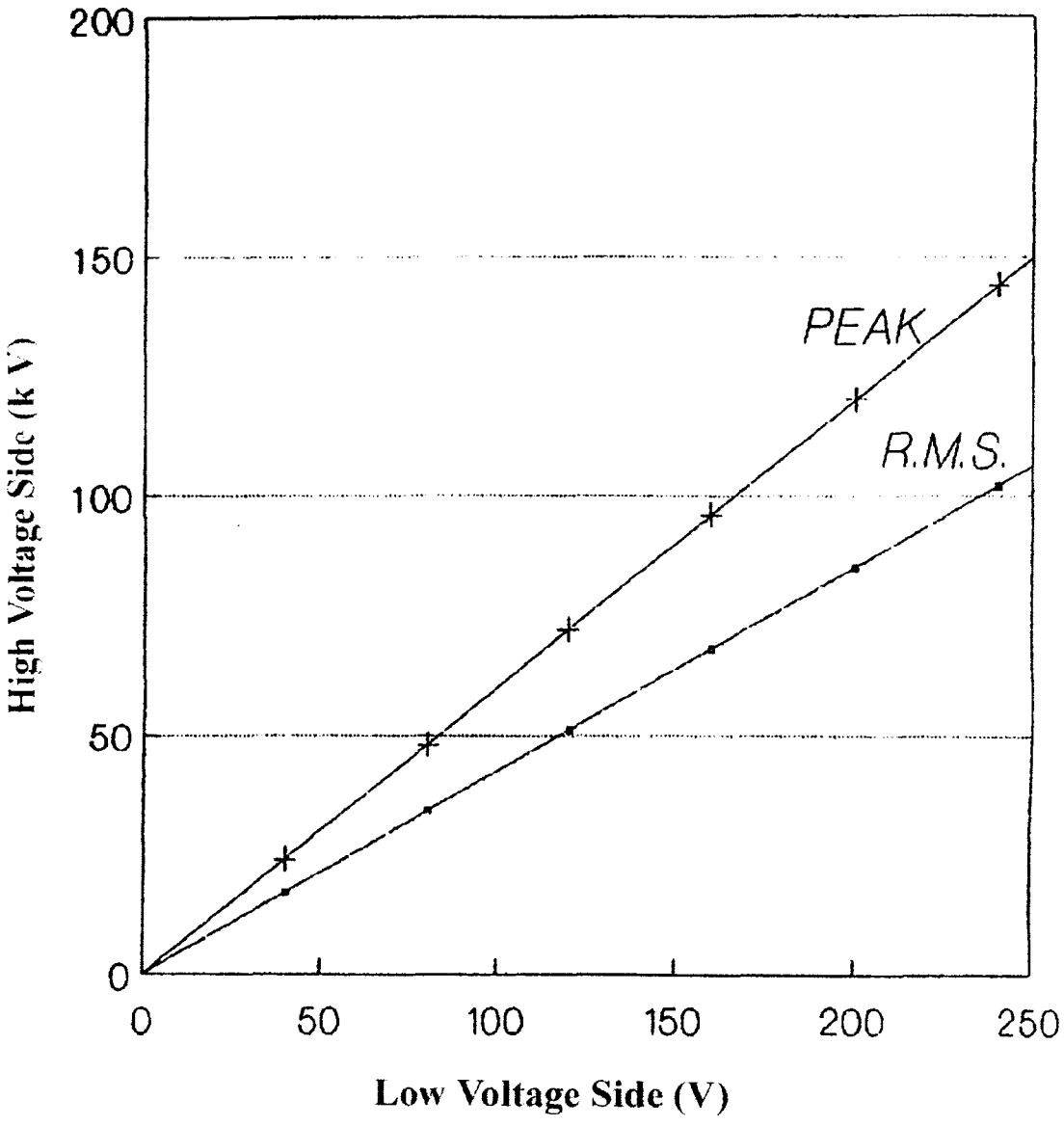


Figure A.2: Calibration Curve for Testing Transformer **[118]**

APPENDIX A-4

The absolute humidity measurement was done using the wet and dry bulb temperature readings and the curve given in Figure 10.1 & 10.2**[119]**. The absolute humidity obtained from the above curve was converted into relative humidity (RH) using the conversion table **[120]**.

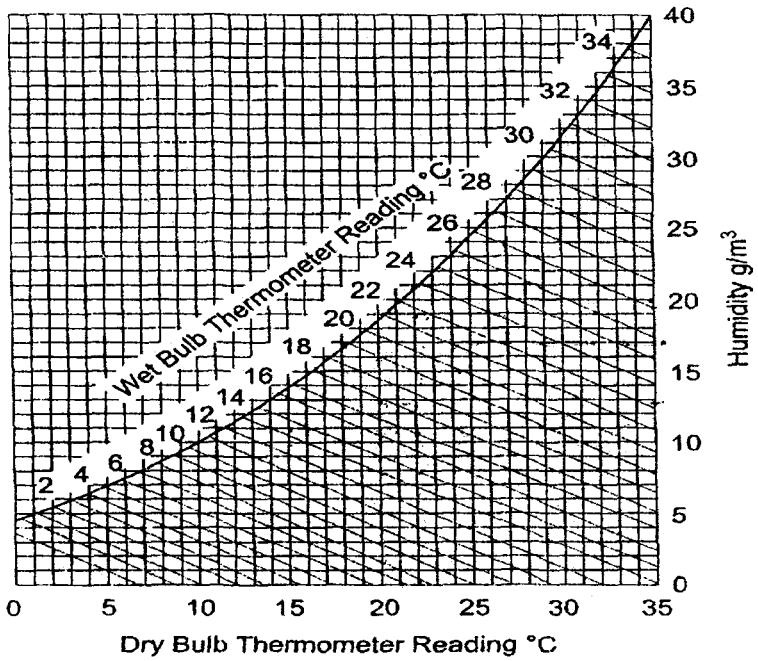
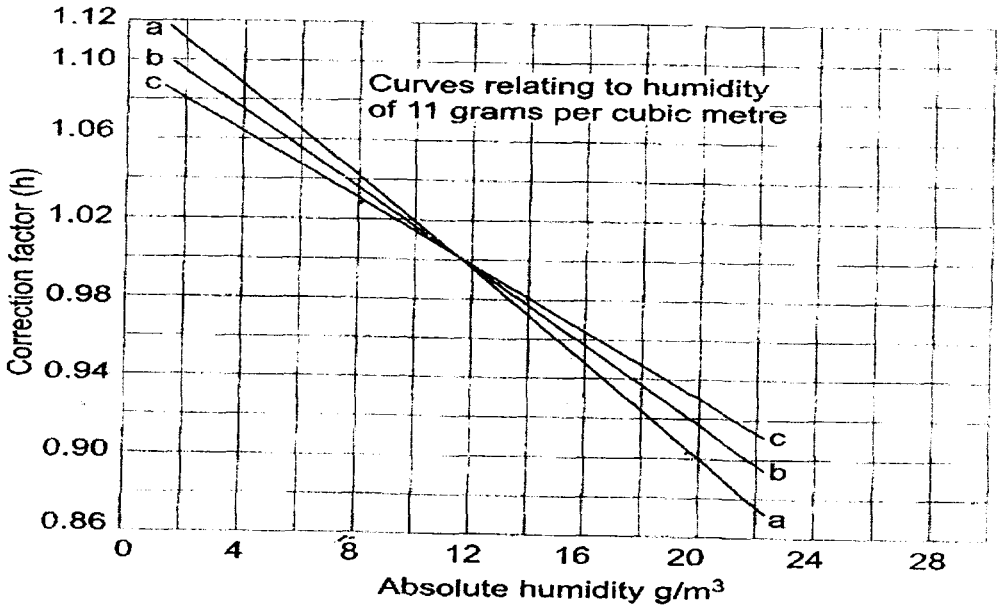


Fig. 10.1 *Computation of absolute humidity from wet and dry bulb thermometer temperatures*



a — For power frequency tests
b — For positive impulse tests
c — For negative impulse tests

Fig. 10.2 *Humidity correction factor*

APPENDIX A-5

This section gives the details of the reasons and effects due to untimely fog that occurred in March 2008 **[124], [125], [126], [127]**

4 Sunday Hindustan Times, New Delhi, March 9, 2008

Metro, train services, water supply hit in city after Northern Grid partially trips

Capital hit hard by untimely fog

Moushumi Das Gupta
New Delhi, March 8

METRO AND train services and water supply were hit in the Capital on Friday after the Northern Grid, from which Delhi draws power heavily, partially tripped.

Reeling under a shortfall of 1,500 MW, almost the entire city except Lutyen's Delhi and some other areas suffered massive outages between six and 11 hours. The worst-affected areas were west and east. Power supply was restored and the situation bought under control by mid-noon.

It was an unusual culprit for this time of the season that was blamed for the breakdown. Senior officials of the Northern Region Load Dispatch Centre (NRLDC) said dense fog and pollutants accumulated on the transmission lines of the Northern Grid and caused massive tripping, disrupting power supply, rail and metro traffic and water supply. Forty-nine transmission lines in the Northern Grid tripped.

A Delhi Transco spokesman said in all, six 400KV lines tripped in Delhi resulting in a shortfall of 1,500MW in the Capital during the early hours of Friday. "At around 4 a.m., the lines carrying power from Rihand, Singrauli, Tala to Dadri and Delhi tripped causing a shortfall of 1,500MW. Forty-nine 400KV Power Grid lines tripped, including six in Delhi area," said the DTL spokesman.

He added, "The Badarpur Thermal Power Station, Rajghat Power House and IP station escaped the breakdown to ensure supply to south and central Delhi. Complete normalisation was only possible after the Dadri Thermal Power Station supplying power to Delhi was restored around noon."

The worst-affected were east and west Delhi. "The lights went off at 1.30 a.m. and came only after 11.30 a.m. We called the local complaint centre but, as usual, the phones lines were put off the hook," said Suhasini Nair, a Patparganj resident. Areas like Mayur Vihar, Vasundhara, Patparganj, Dwarka, Janakpuri, Paschim Vihar, Pitampura, Daryaganj went without power for 10 hours at a stretch.

This is not the first time power lines in the Capital tripped due to fog. "It's a recurrent problem during winter months. But we were not expecting it during this time of the year. Apart from the fog, what aggravated the problem was the high humidity content. Moisture accumulated in the 400KV transmission lines, which resulted in tripping," said a power department official.

moushumi.gupta@hindustantimes.com

Good old diesel engines to rescue

HT Correspondent
New Delhi, March 8

THE RAILWAYS, perhaps for the first time, used diesel-run locomotives to pull electric-run local trains like tow-away vehicles, and kept services afloat when the power grid collapse severely affected the rail network.

Power supply to the rail network was unavailable for two to four hours in the morning. "The priority were local trains in the morning because they bring thousands of people into the Capital from different parts every day," said a senior railway official. Since electricity was scarce and the demand high, the movement of all goods trains was temporarily suspended. As an additional measure, all long-distance trains heading towards Delhi were instructed to stop at suburban stations to accommodate daily passengers.

Metro services affected

Tripping of six transmission lines in Delhi also affected the Metro services. According to Delhi Metro Rail Corporation (DMRC) officials, the voltage suddenly dipped causing disruption of metro at about 6.30 a.m. on Line 1 (Shahdara-Rithala) and Line 3 (Indraprastha-Drawka).

A senior DMRC official said the disruption of metro service was for a very few minutes. The situation was immediately normalised, by drawing the supply from metro's Indraprastha and New Delhi sub-stations.

letters@hindustantimes.com

Fog trips Northern Grid

Twenty-five trains, including Rajdhani, Shatabdi delayed

New Delhi, March 7

LARGE PARTS of the capital went without power since early morning on Friday as 50 supply lines of the Northern Grid, which supplies power to Delhi and neighbouring areas, tripped due to fog.

A six-hour power outage followed by another six hours for electricity supply to be restored affected most parts of Central, East and South Delhi and train services.

A spokesman for the Northern Regional Load Dispatch Centre (NRLDC) of the Power Grid Corporation said 50 lines of 400 kv in Delhi's Bawana-Bamroli-Mandola line, western Uttar Pradesh and Haryana tripped at about 3 a.m. The system was restored at about 9 a.m., he added.

The engineers were suspecting the snag was due to heavy fog that had got the high-tension wires wet.

Train movement in the national capital and its vicinity was also affected due to the power cut. "Traffic in the region was badly affected by the power failure, with the worse affected sections being Ferozabad-Dadri and Tughlakabad-Palwal lines, where electricity supply was disrupted since 3.45 am and 6.15 am respectively," a senior Railway official said.

"The electricity supply to the overhead cable, which supplies power to the engine, was completely down, bringing the movement of trains to a halt," he added.

The officials said the Railways was taking all emergency measures and diesel engines were being dispatched to resume services.

Rajeev Saxena, chief public relations officer of Northern Railways said 25 trains had been delayed in a big way, including Rajdhani and Shatabdi trains between the capital and various cities. However, trains from New Delhi, Nizamuddin and Delhi stations that were scheduled for the afternoon and evening would leave as per schedule.

Agencies

अमर उजाला

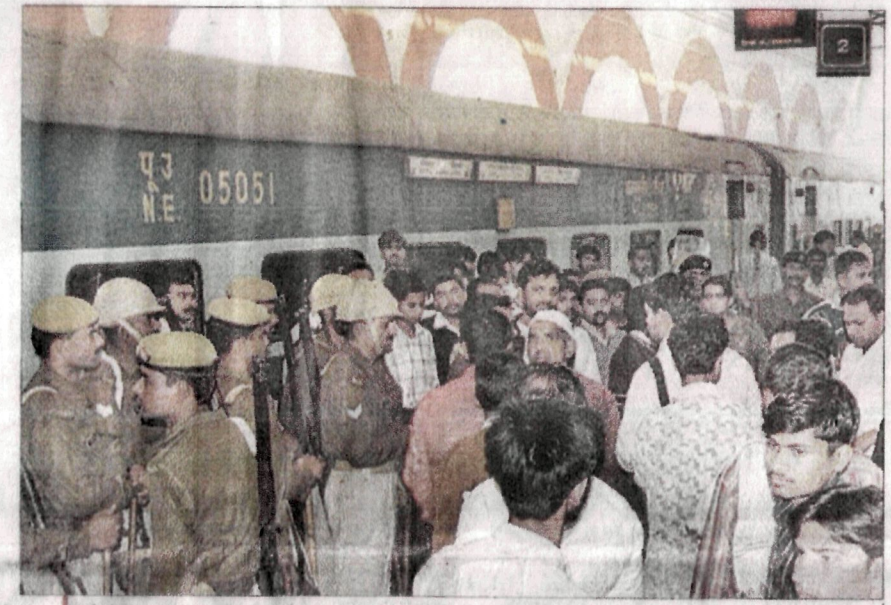
● कोहरे और प्रदूषण ने रोकी बिजली

जाम हुई जिंदगी

● उत्तरी राज्यों में कई मार्गों पर ट्रेनें थमीं

नई दिल्ली/लखनऊ/अलीगढ़ । बढ़ते प्रदूषण और कोहरे के कारण शुक्रवार को उत्तरी ग्रिड की दर्जनभर बिजली लाइनें ट्रिप कर गईं। बिजली गुल हुई तो उत्तरी राज्यों में ट्रेनें भी थम गईं। रेल यातायात बुरी तरह चरमरा जाने से सुबह अपने घर से दफ्तर, स्कूल, कॉलेज और कारोबार के लिए निकले हजारों यात्री जहां थे वहीं रुके रहे। नतीजतन उत्तरी राज्यों खासतौर पर दिल्ली, वेस्ट यूपी और हरियाणा में लगभग 10 घंटे तक बिजली नदारद रहने से जिंदगी जाम हो गई।

कोहरे के कारण उत्तरी ग्रिड में गड़बड़ी बृहस्पतिवार आधी रात से ही शुरू होने लगी थी। सबसे पहले मैनपुरी-कानपुर की पारेषण लाइन में गड़बड़ी आई। उसके बाद रात तीन बजे से उत्तरी ग्रिड की आपस में जुड़ी अन्य लाइनें भी ट्रिप करती चली गईं। फिरोजाबाद-दादरी, बल्लभगढ़, बहादुरगढ़ से लेकर तुगलकाबाद-पलवल समेत हरियाणा और पश्चिमी उत्तर प्रदेश को जाने वाली पारेषण लाइनों में गड़बड़ी शुरू हो गई। अलीगढ़, यूपी के गाजियाबाद, गौतमबुद्ध नगर, मेरठ, बुलंदशहर, मुजफ्फरनगर, आगरा, मथुरा, सहारनपुर आदि जिले अंधकार में डूब गए। बिजली गुल होने से गाजियाबाद, अलीगढ़ और मथुरा में ट्रेनें जहां की तहां रुक गईं। हाथरस में कई ट्रेनों के रुकने पर यात्रियों को पांच घंटे परेशानी झेलनी पड़ी। अलीगढ़ में घंटों फंसे रहे यात्रियों ने स्टेशन पर हंगामा किया। यहां पर दो बार विद्युत आपूर्ति बंद होने से ट्रेनें रुकी रहीं। विद्युत आपूर्ति ठप होने से फिरोजाबाद-दादरी और तुगलकाबाद-पलवल मार्ग बुरी तरह प्रभावित हुआ। दिल्ली-हावड़ा रेलमार्ग पर गाजियाबाद से कानपुर के बीच राजधानी और शताब्दि समेत 40 से अधिक ट्रेनें जहां थीं वहीं रुक गईं। रेलवे के अनुसार 65 मेल और एक्सप्रेस ट्रेनें आठ से दस घंटे देर से पहुंचीं। रेलवे के सीपीआरओ राजीव सक्सेना ने बताया कि सबसे पहले दिल्ली-एनसीआर में लोकल ट्रेनों के परिचालन को पटरी पर लाया गया। सुबह कोहरा छंटने के बाद बंद लाइनों और उपकेंद्रों को चालू करने की प्रक्रिया शुरू हुई। पावर कॉरपोरेशन के निदेशक वितरण एवं पारेषण अरुण ने बताया कि कोहरे की वजह से समस्या पैदा हुई। हालांकि उत्तरी ग्रिड लोड डिसपेच सेंटर के कार्यकारी निदेशक एस.के. सोनी का दावा है कि सुबह दस बजे तक लगभग पूरी गड़बड़ी को दूर कर लिया गया। ब्यूरो ▸ संबंधित सामग्री पेज 2 और 5 पर



परेशान : अलीगढ़ रेलवे स्टेशन पर परेशान यात्रियों को समझाते पीएसी और जीआरपी के जवान। *अमर उजाला*

बुरा हाल

- उत्तरी ग्रिड फेल होने से लगभग दस घंटे तक हरियाणा, यूपी दिल्ली मार्गों में रेल यातायात पर असर
- दिल्ली-हावड़ा फीरोजाबाद-दादरी तुगलकाबाद-पलवल मार्ग बुरी तरह प्रभावित
- राजधानी और शताब्दी समेत 40 से अधिक ट्रेनें जहां की तहां रुकी रहीं
- बिजली आपूर्ति बहाल होने के बाद भी अधिकांश ट्रेनें घंटों विलंब से चल रही हैं
- लंबी दूरी के यात्रियों समेत सुबह रोजाना दफ्तर, स्कूल, कॉलेज और कारोबार के लिए सफर करने वाले रहे घंटों परेशान

प्रदूषण से पैदा हो रहा बिजली संकट

उत्तरी राज्यों में अब बढ़ते प्रदूषण और कोहरे से बिजली संकट पैदा हो गया है। पॉवर ग्रिड को इसके कारण अपनी ट्रांशमिशन लाइनों को बचा पाना मुश्किल हो रहा है। राजस्थान, हिमाचल प्रदेश, उत्तराखंड और जम्मू-कश्मीर में प्रदूषण कम होने के कारण वहां हालात गंभीर नहीं हुए। लेकिन बाकी राज्यों को लगभग 10 घंटे बिना बिजली के रहना पड़ा

वजह :

■ लगातार बढ़ते प्रदूषण से ट्रांशमिशन लाइनों पर जमी धूल बिजली आपूर्ति में बाधा बन जाती है

■ वातावरण में आद्रता 85 फीसदी से ज्यादा होने और तापमान 10-12 डिग्री या उससे नीचे चले जाने पर ग्रिड के इंसुलेटर और फ्लैशओवर काम करना बंद कर देते हैं

बाधा :

■ पावर ग्रिड हालांकि हर साल ट्रांशमिशन लाइनों पर जमी धूल की सफाई करने का दावा करता है

दिसंबर 2005 में कोहरे के कारण पूरे उत्तरी ग्रिड के फेल हो जाने के बाद केंद्र सरकार ने इन लाइनों की धुलाई के लिए हेलीकॉप्टर सेना लेने की योजना बनाई थी

जोखिम भरा कार्य होने के कारण योजना फाइलों में दबी रह गई

400 केवी जैसी उच्च क्षमता की लाइनों की सफाई के लिए अभी तक खास प्रौद्योगिकी उपलब्ध नहीं

उत्तरी ग्रिड में अंधेरा

■ 6 फरवरी 2008 : कई लाइनों में गड़बड़ी आई

■ 4 जनवरी 2008 : कोहरे के कारण कई लाइनें ट्रिप कर गई

■ 14 दिसंबर 2007 : कोहरे के कारण 400 केवी क्षमता की लगभग एक दर्जन ट्रांसमिशन लाइनें ट्रिप कर गई

■ 23 दिसंबर 2005 : पूरा उत्तरी ग्रिड फेल हो गया। लगभग 20 घंटे बाद बिजली बहाल हो पाई

■ 18 दिसंबर 2002 : 400 केवी की कई लाइनें ट्रिप कर गई थीं

■ 2 जनवरी 2001 : दिल्ली समेत पूरे उत्तरी भारत में बिजली गुल हो गई थी

हरियाणा और राजस्थान के तय सीमा से ज्यादा बिजली लेने के कारण भी दबाव बढ़ा

ग्रिड फेल होने से अंधेरे में डूबे रहे उत्तरी राज्य

नई दिल्ली। प्रदूषण और कोहरे के कारण शुक्रवार सुबह उत्तरी राज्य अंधेर में डूब गए। तापमान में कमी और पारेषण लाइनों पर जमीं धूल ने बिजली आपूर्ति बाधित कर दी। उत्तरी पॉवर ग्रिड को इस गड़बड़ी को ठीक करने में घंटों लग गए।

उत्तरी ग्रिड इस गड़बड़ी की मुख्य वजह पारेषण लाइनों और इंसुलेटरों पर प्रदूषण से जमी धूल को बता रहा है। आमतौर पर राज्यों द्वारा ग्रिड से अपने कोटे से ज्यादा बिजली लेने पर ही ग्रिड में गड़बड़ी की आशंका रहती है। लेकिन इस बार प्रदूषण और कोहरा मुख्य वजह रहे। पावर ग्रिड के अध्यक्ष और प्रबंध निदेशक आर. पी. सिंह ने बताया कि इस साल सर्दियों में बारिश न होने के कारण पारेषण लाइनों पर जमी धूल की प्राकृतिक तौर पर धुलाई नहीं हो पाई है। अब जबकि तापमान 30 डिग्री से ज्यादा हो चुका है धूल भी ज्यादा उड़ रही है। लेकिन रात में तापमान कम होने से नमी भी है। नमी के कारण धूल पारेषण लाइनों और इंसुलेटरों में गड़बड़ी की वजह बन रही है। हालांकि उन्होंने दावा किया कि पावर ग्रिड की सतर्कता के कारण पूरा ग्रिड ट्रिप होने से बच गया। उन्होंने कहा कि प्रदूषण के कारण बिजली लाइनों को यह खतरा लगातार बना हुआ है। इससे पहले बीते वर्ष दिसंबर और इस साल जनवरी-फरवरी में भी कुछ लाइनों पर कोहरे की मार पड़ चुकी है। ब्यूरो

मुसीबत

हरियाणा, दिल्ली और प. यूपी में ज्यादा संकट

लाइनों पर जमी धूल से बाधित हो रही बिजली

अलीगढ़, 10 मार्च, 2008

महानगर
वर्ष 2 अंक 46
पृष्ठ : 16
मूल्य : तीन रुपये

अमरउजाला

आगरा • बरेली • मेरठ • मुरादाबाद • कानपुर • देहरादून • इलाहाबाद • झांसी • चंडीगढ़ • वाराणसी • जालंधर • नई दिल्ली • जैनीताल • जम्मू • धर्मशाला • अलीगढ़ • गोरखपुर

उत्तरी ग्रिड पर तीन दिन में दूसरी बार कोहरे और प्रदूषण की मार, कई लाइनें ट्रिप

फिर ठप

दिल्ली, हरियाणा और उत्तर प्रदेश में घंटों बिजली नदारद, ट्रेनें थमी; जलापूर्ति बाधित

संकट

ट्रेनें ठप होने से स्टेशनों पर यात्रियों का हुजूम जमा हो गया। तस्वीर में टिकट लौटाने का नजारा अलीगढ़ का है।

आशंका

उत्तरी ग्रिड की गड़बड़ी को फैलने से रोक लिया गया है, मगर आगे भी संकट रहने की आशंका है

35 लाइनें उत्तरी ग्रिड की ट्रिप कर गईं थीं, जिसकी वजह से यह परेशानी खड़ी हुई

10 घंटे से ज्यादा बिजली नदारद रही। दिल्ली, हरियाणा और यूपी बुरी तरह प्रभावित

20 से ज्यादा ट्रेनें बिजली बाधित होने की वजह से जहां की तहां रुक गईं

10 घंटों तक लेट रहीं ट्रेनें। कई सुपरफास्ट ट्रेनें तो 30 किमी/घंटा की रफ्तार से रेंगी

3 दिन में यह दूसरी बार है जब उत्तरी ग्रिड में गड़बड़ी की वजह से अंधेरा छा गया है

नई दिल्ली। राजधानी दिल्ली समेत उत्तर प्रदेश और हरियाणा में रविवार को जिंदगी एक बार फिर ठप पड़ गई। अभी शुक्रवार को ही उत्तरी ग्रिड में गड़बड़ी ने रफ्तार पर ब्रेक लगा दिए थे, अब रविवार को एक बार कोहरे और प्रदूषण की मार से उत्तरी ग्रिड की 35 ट्रांसमिशन लाइनें ट्रिप कर गईं। तीन राज्यों में 10 घंटे तक बिजली नदारद रही। ट्रेनों के पहिये थम गए, जलापूर्ति बुरी तरह प्रभावित हुई। हालांकि पावर ग्रिड ने इस गड़बड़ी को पूरी ग्रिड तक फैलने से रोक लिया, मगर अभी यह संकट आगे भी बने रहने की आशंका है।

तापमान अचानक बढ़ जाने तथा रात में नमी जारी रहने के कारण ट्रांसमिशन लाइनों पर बिजली दौड़ा पाना कठिन हो रहा है। बीते शुक्रवार से उत्तरी ग्रिड में संकट जारी है। क्योंकि ट्रांसमिशन लाइनों और इंसुलेटरों पर प्रदूषण से जमी धूल बिजली को आगे ले जाने में सबसे बड़े अवरोधक बन गए हैं। रविवार को भी ऐसा ही हुआ। हो गई थी। तब उत्तरी ग्रिड में 26,180 मेगावाट बिजली की मांग थी। हालांकि उपलब्धता मात्र 23,245 मेगावाट ही थी। इस तरह उत्तरी राज्य तब 2935 मेगावाट बिजली की कमी से भी जूझ रहे थे। बारिश नहीं होने से किसान भी खेती के लिए ज्यादा बिजली का इस्तेमाल कर रहे हैं। इससे ग्रिड पर भी लोड बढ़ा था। लेकिन रात बीतते बीतते ग्रिड की लाइनों में गड़बड़ी बढ़ती चली गई और कुल 35 लाइनें ट्रिप कर गईं। यह लाइनें दिल्ली, हरियाणा और पश्चिमी उत्तर प्रदेश की थीं। चूंकि प्रदूषण भी इन राज्यों में ज्यादा है। इसलिए इनकी बिजली लाइनों पर ज्यादा संकट आया। इस गड़बड़ी की वजह से दिल्ली-कानपुर सेक्शन में रेल सेवाएं बुरी तरह प्रभावित हो गईं। पूरे रेलखंड में दर्जनों ट्रेनें घंटों एक ही स्थान पर खड़ी रहीं। शताब्दी समेत कई ट्रेनें तीन से दस घंटे तक लेट चलीं। अलीगढ़, हाथरस मेरठ, सहारनपुर, मुजफ्फरनगर, बागपत, बिजनौर में कई घंटे बिजली नहीं आई और जलापूर्ति भी बाधित रही। मुजफ्फरनगर में गुस्साए व्यापारियों ने बिजली विभाग के अधिकारियों का पुतला भी फूंका। आगरा-दिल्ली रेलवे लाइन पर वृंदावन रोड स्टेशन के पास एवं यमुना ब्रिज-टूंडला के मध्य दो स्थानों पर ओएचई टूट जाने की घटना ने 'कोढ़ में खाज' का काम किया। दिल्ली की ओर से आने वाली ट्रेन शताब्दी, ताज एक्सप्रेस, छत्तीसगढ़, पंजाब मेल आदि पांच से छह घंटे लेट आगरा पहुंचीं। मथुरा और अलीगढ़ में ट्रेनों का बुरा हाल रहा। दिल्ली-हावड़ा रूट के साथ ही कानपुर

कैसी ये कोहरे की मार

- उत्तर भारत के तापमान में अचानक कुछ गिरावट से कोहरा बनने लगा है
- इसके साथ ही इस इलाके में बढ़ते प्रदूषण ने दिक्कत बढ़ा दी है
- कोहरे की वजह से बिजली ट्रांसमिशन में बाधा आने लगी है
- प्रदूषण से इन लाइनों पर जमी धूल से समस्या और गहरा गई है
- जाड़े की बारिश से होने वाली लाइनों की प्राकृतिक धुलाई इस बार नहीं हुई है

संडे मूड पर बिजली

अलीगढ़ में दस घंटे बिजली गुल

अलीगढ़। उत्तरी ग्रिड में आई खराबी के कारण रविवार को भी बिजली संकट गहरा गया। तड़के साढ़े तीन बजे से बिजली गड़बड़ाना शुरू हो गई थी और पांच बजे तक पूरे शहर की बिजली आपूर्ति ठप हो गई। इससे कई क्षेत्रों में पेयजल संकट भी गहरा गया। विद्युत परिषण अधिकारी व स्टाफ ने गांधी पार्क क्षेत्र को छोड़कर दोपहर दो बजे तक विद्युत आपूर्ति को सुचारु किया।

हरदुआगंज से 220 केवी खुर्जा को दो सर्किट के माध्यम से बिजली दी जाती है। हरदुआगंज से जिन दो सर्किटों से बिजली खुर्जा को दी जा रही थी, उनमें से सर्किट प्रथम 3.28 बजे बंद हो गया।4.16 बजे दूसरा सर्किट भी ठप हो गया। फलस्वरूप 132 केवी खुर्जा से बीनेर की सप्लाई बंद हो गई। इसके बाद 4.18 बजे बीनेर को सासनील से जोड़कर बिजली दी गई, लेकिन 4.55 बजे से सासनील की जिन दो सर्किटों से हरदुआगंज से बिजली आ रही थी, उनमें से एक सर्किट बंद हो गया। इसके साथ ही 132 केवी खैर परिषण केंद्र की बिजली भी बंद हो गई। शेष पेज 3 पर

गड़बड़ियां

हरदुआगंज को हर तरफ से हुई आपूर्ति बंद

मीतई से बिजली देकर मशीनें चालू कराई गईं

▸ पांच घंटे ट्रेनें फिर जाम हुईं पेज 7 पर
▸ किसी की परीक्षा सूटी तो किसी की शादी लेट!

APPENDIX A-6

The below tableA.1 gives range of various ions that are found in water of Aligarh district. The pH of water ranges between 6.9-8.1 **[129].**

Table A.1

Cation/Anion	Quantity (mg/L)
Sodium ion (Na^+)	74 -313
Potassium ion (K^+)	10 -52
Calcium ion (Ca^{2+})	10 - 78
Magnesium ion (Mg^{2+})	5 -110
Bicarbonate ion (HCO_3^-)	60 - 500
Carbonate ion (CO_3^{2-})	0 - 200
Chloride ion (Cl^-)	42 - 205
Nitrate ion (NO_3^{2-})	6 - 21
Sulphate ion (SO_4^{2-})	82 - 740

APPENDIX A-7

The Hindu, 17th Feb. 2009

Washing power transmission lines using helicopters

'If it is foggy or windy it is difficult to fly, hold the machine steady near towers'

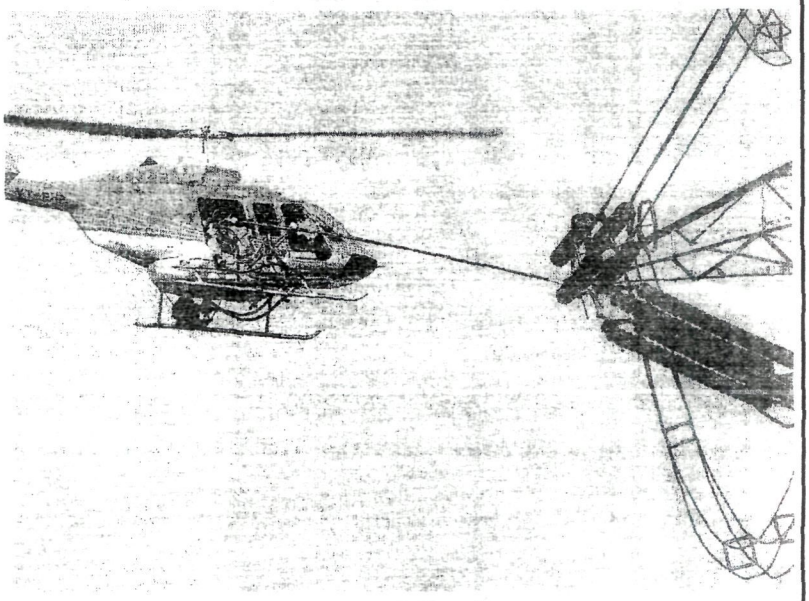
Smriti Kak Ramachandran

NEW DELHI: The hazards associated with his job are the last thing on Charles Pooley's mind when he is manoeuvring his helicopter around high-tension power wires 300 feet above the ground. Mr. Pooley, a skilled pilot who has logged more than 35,000 hours over the past 35 years, is currently in India as part of ongoing trials for using helicopters to wash the insulators of critical high-tension wires.

"It is a job. I don't think of it as dangerous," Mr. Pooley told *The Hindu* on the sidelines of a live demonstration at Ballabgarh on Monday. The Australian pilot, who has conducted similar exercises over the past three years in various parts of the world including the US, Africa and China, said all that he requires to carry out his task on Indian soil is "good logistical support." "We need the weather to be conducive. If it is foggy or windy it is difficult to fly and hold the machine steady near towers while the insulators are being washed," he said. The practice, being carried out in India for the first time by Power Grid, was introduced last November. "Even though the procedure is extremely expensive, it is an effective way of washing insulators on critical lines in difficult terrain where manual washing is time consuming and tricky," said Bhaskar Sharma, general manager of the Power Grid Corporation of India. Power Grid has tied up with Pawan Hans Helicopters for the exercise to prevent the tripping of power lines because of high pollution, fog and bird droppings. In winter, dense fog in the northern parts of the country along with heavy pollution, bird droppings and dust results in tripping of a large number of lines causing grid instability, Power Grid officials explained. "Last year in March we had several such trippings and we decided to take remedial measures this year prior to the onset of winters," said Pankaj Kumar, additional general manager (operations) of Power Grid.

While the exercise in itself has fetched favourable results, the only deterrent so far has been the prohibitive cost. "We have to rely on foreign pilots because we do not have any trained pilots in India who can carry out the task," said Mr. Kumar.

Power Grid has to cough up a whopping Rs.8.2 crore to Pawan Hans for six months clocking 300 flying hours. "Five helipads at Meerut, Dadri, Panipat and Ballabgarh have been prepared and since November we have already washed 1,500 towers," said Mr. Kumar.



SHOW OF SKILL: *A helicopter deployed by Power Grid Corporation of India demonstrating live line washing of insulators of critical transmission lines for the first time in India at the Ballabgarh power sub-station in Haryana on Monday.* - PHOTO: S. SUBRAMANIUM

Publications

PUBLICATIONS

International Conferences:

1. **Asfar Ali Khan** et al, *"Effect of Contaminant pH and Natural Fog on Naturally Polluted Porcelain Disc Insulator in Northern Region of India"*, Accepted for publication and presentation at 2009 International Conference on Electric Insulation and Dielectric Phenomena **(CEIDP 2009)** to be held, 18 -21 October 2009, Virginia Beach, USA.
2. **Asfar Ali Khan** et al, " *A study of flashover voltage of artificially polluted porcelain disc insulators under natural fog conditions*" Presented and published in the Proceedings of 2008 International conference on condition monitoring and diagnosis **(CMD2008),** Beijing China , 21-24 April 2008,pp 369-371.

National Conferences:

1. **Asfar Ali Khan** et al *"Dependence of FOV on pH value and conductivity of contaminants on porcelain disc insulators"*, Proceedings of IDEA-07, BGIET, Sangrur, 2-3 March, 2007, pp 121-124.

2. **Asfar Ali Khan** et al, *"Dependence of flashover voltage on pH value of contaminants on porcelain disc insulators"* Proceedings of National conference on Advancement of Technologies (ADTECH), GLA Institute of Technology and management, Mathura, 25-26 February 2007, pp 148-153.

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Effect of Contaminant pH and Natural Fog on Naturally Polluted Porcelain Disc Insulator in Northern Region of India

Asfar Ali Khan*, Ekram Husain and Aejaz Masood
Department Of Electrical Engineering, Aligarh Muslim University, Aligarh, India
*Email: aa.khan.ee@amu.ac.in

***Abstract*—Overhead power transmission lines cross regions which are different in environmental conditions. The reliable and uninterrupted operation of modern power system depends on reliable insulation. Outdoor insulation cannot be selected without having knowledge of prevailing pollution severity. This paper reports results of natural pollution tests that have been done at different locations. Flashover voltage (FOV) of porcelain disc insulator for different pH values and conductivity has been recorded to relate FOV with pH and conductivity of the contaminants. It is found that a decrease in pH and increase in conductivity of the contaminant lowers FOV of the insulators. Regular condition monitoring of porcelain insulators can be done using pH of the contaminants as an effective pollution severity indicator, it may further be used for devising proper maintenance schedule.**

***Key Words:* Porcelain insulators, Pollution test, Flashover Voltage, pH value, Conductivity, ESDD.**

I. INTRODUCTION

The reliable and uninterrupted operation of modern power system depends on reliable and satisfactory performance of insulators under different environmental conditions. Contamination induced flashover is the most serious problem with high voltage insulators. The major contributors to environmental pollution are dust, dirt, industrial emissions, vehicular pollution, saline deposits, desert salts etc. These contaminants, under damp conditions interact with water, which then behaves as an important pollutant vis-à-vis insulation capability [1].

Selection of outdoor insulation in a new environment is a difficult task. In addition, an area where transmission lines already exist, economical frequency of maintenance procedure is important. Both these objective necessitates assessment and measurement of pollution severity of an area. The known methods employed for pollution severity measurement as given [2] includes ESDD measurement, conductivity measurement without removing contaminant, chemical analysis, leakage current measurement, use of directional deposit gauges.

The pollution characteristics of the design of insulators used in transmission systems are, in general, known only from service experience supplemented by tests on a few insulators in the laboratory or in naturally polluted sites. The performance of insulators can be assessed by natural pollution tests, which are imprecise but realistic, and by artificial tests, which are much more precise but less realistic [3].

This paper describes results of experiments conducted on naturally polluted insulators under natural fog conditions. As reported earlier [4], pH of the contaminant affects the flashover characteristics. To understand effect of pH on naturally contaminated insulators, this study was undertaken wherein porcelain disc insulators were installed at three different locations that differed in their emission levels. Conductivity, pH (defined as the negative logarithm of the hydrogen ion activity of the solution of the contaminant) and flashover voltage of the contaminant was measured. The results were indicative of the fact that pH, in addition to conductivity (ESDD) can also be used as a pollution severity indicator.

II. EXPERIMENTAL PROCEDURE

In order to carry out the investigation, three typical locations representing a road highway, an area near thermal plant and a residential area have been selected in and around Aligarh (India). The three locations are separated by about 15 miles. Aligarh lies in the northern Indian state of Uttar Pradesh. It lies in subtropical climatic zone with location at 27.88°N latitude and 78.08°E longitude at height of 178m above mean sea level. The city has hot and dry summer with mean temperature between 32.2-33.8°C; the mean winter temperature ranges between 12.2- 15.0°C. Aligarh has intermittent rainy season with an annual average rainfall of around 850mm. The description of the locations and the related probable types of pollution are given in Table I

Table I

Location	Description of the location
1	A site outside of the city at an electrical substation at Sarsaul on national highway (NH 91) that connects Kanpur to Delhi with a very heavy traffic (vehicular pollution, dust, agricultural pollution)
2	A site very near to a coal fired thermal power plant at Kasimpur ,Harduaganj, Aligarh (Fly ash, dust, agricultural pollution, low vehicular traffic)
3	A residential area at Nishat Apartments, Aligarh (no industry nearby , very low vehicular traffic)

III. SAMPLE PREPARATION

In the present study, test were carried out using the cap and pin type insulators that are extensively used in overhead networks in India. The unit diameter is 254 mm, spacing 127 mm and leakage distance 290 mm.

The surfaces of the specimen insulator were cleaned and washed with detergent to remove repellency. The pretreated insulators were installed at the locations given in table I. The investigation was initiated by installing the cap and pin type

insulator in each of the three selected locations in first week of July 2006. The test insulators were positioned at almost the same height as of the line insulators, without voltage being applied, and were left to natural pollution. The samples were periodically removed in December 2006, December 2007, and March 2008 for testing. The samples at the end of the desired exposure period were brought to the high voltage laboratory for measuring the desired parameters. The naturally polluted insulators were left to get wet overnight under natural conditions of dew and fog from 6 pm to 8 am.

IV. MEASUREMENT

The flashover voltage of the sample was measured in morning hour (Temperature around 15 - 20°C & pressure 740 mm Hg) using high voltage testing transformer. The contaminants were removed from the sample and the pH and conductivity of the pollutant measured.

A. Voltage Measurement

The high voltages were obtained from a testing transformer of 150 kV, 50 Hz, 1-phase, 30 kVA rating. The short circuit current of the testing transformer is 15 A at maximum excitation. The voltages were measured using a voltmeter (accuracy ± 1%) connected to the primary side of the transformer, that reads the low side voltage. The corresponding high voltages are obtained from a calibration curve [5] drawn by using the sphere – sphere electrode system having diameter of 25 cm (IS: 1876-1963) [6].

B. Measurement of pH

The pH value of the contaminant was measured after removing deposited salt on the sample using LI 120 pH meter with range from 0-14.

C. Measurement of Conductivity

The conductivity of the contaminant deposited on the surface of the insulators was measured using CM 180 conductivity meter having cell constant 0.1 to 1 and conductance range 20 µS to 200 mS.

D. ESDD Calculation

Since electrical condition along contaminated surface is because of ionic conduction in aqueous solution of salts, the quantity of potentially conducting soluble material is conventionally described by an equivalent amount of NaCl or equivalent salt deposit density (ESDD) [7]. ESDD value is obtained from measurements of volume conductivity, solution temperature and volume of wash water solution using equation (5) [8].

V. RESULTS AND ANALYSIS

The contaminated insulators after being exposed to natural wet conditions were subjected to high voltage for recording wet flashover voltage. The observed value of flashover voltages per unit insulation distance (FOVUID), conductivity and pH are given in Tables II-X

The variation of FOVUID and pH value of the contaminant for different locations is given in Figure 1-3. Figure 1-3 shows that as pH of the contaminant increases, there is increase in FOVUID values. This is due to the reason that as pH increases there is decrease in the hydrogen ion concentration implying less acidic nature of the electrolytic solution. Since pH is based on logarithmic scale, a change of 0.4 pH implies about 2.5 fold change in hydrogen ion concentration. It can also be inferred that although the three locations are separated by about 15 miles, there is difference in pH value of the contaminant. This may be due to difference in the nature of deposits at the three locations. At location 1, the deposit consists of dust, tiny particles of carbon, ash, oil formed by incomplete combustion of fuel. Near thermal plant the insulators in addition to dust are also subjected to fly ash deposits that consist mainly of SiO_2, Al_2O_3, Fe_2O_3, CaO. MgO,P_2O_5 ,carbon and carbonate ions.

Figure 4-6 shows that as ESDD increases FOVUID values drop. Although the three locations lie in very light to light range of pollution severity [10], the fall in FOVUID at location 3 is least and so it is relatively least polluted. It is also observed that in spite of location 2 samples showing higher ESDD for the entire test, the FOVUID values are almost similar to that of location 1. This is probably due to the characteristics of the inert ash deposited on the samples; this ash forms an inert matrix and impedes the flow of leakage current.

It is worth mentioning that the maximum drop in FOVUID values are for the samples tested in March 2008. This may be due to the reason that during the period December 2007 and March 2008 normal winter rains did not occur; thereby self cleaning of insulator surface did not happen leading to substantial deposits on the insulator. Apart from this, the relative humidity was very high during the first week of March 2008. Unusual fog conditions prevailed on 6th, 7th and 8th March 2008, the days when testing of samples was done [11]. The increased deposition and fog aggravated the stress condition that led to failure of insulators. Thus in addition to high ESDD, higher values of relative humidity plays a vital role in lowering the voltage at which the insulator flashes over due to the reason that at higher relative humidity the availability of dissociated water ions increases.

Table II
Location 1 December 2006

Sample	pH	σ (µS/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.90	92.35	0.0304	3.114
2	6.88	96.15	0.0317	3.081
3	6.86	99.39	0.0328	3.049
4	6.81	102.27	0.0338	3.016
5	6.77	106.05	0.0351	3.000
6	6.74	107.80	0.0357	2.983
7	6.72	110.42	0.0366	2.95
8	6.67	112.15	0.0372	2.934

Table III
Location 1 December 2007

Sample	pH	σ (μS/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.92	114.10	0.0374	3.114
2	6.89	117.04	0.0384	3.081
3	6.89	119.38	0.0392	3.032
4	6.85	121.73	0.0400	3.016
5	6.81	123.78	0.0407	3.000
6	6.79	126.99	0.0418	2.967
7	6.76	130.79	0.0431	2.950
8	6.72	135.47	0.0447	2.934

Table IV
Location 1 March 2008

Sample	pH	σ (μS/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.92	140.18	0.0474	2.786
2	6.90	145.31	0.0492	2.754
3	6.85	146.44	0.0496	2.721
4	6.83	148.71	0.0504	2.672
5	6.79	150.42	0.0510	2.606
6	6.75	152.97	0.0519	2.573
7	6.73	156.66	0.0532	2.540
8	6.67	160.62	0.0546	2.491

Table V
Location 2 December 2006

Sample	pH	σ (μS/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.83	132.25	0.0436	3.213
2	6.77	137.21	0.0453	3.196
3	6.73	139.25	0.0460	3.180
4	6.68	139.84	0.0462	3.147
5	6.64	143.34	0.0474	3.131
6	6.59	147.11	0.0487	3.098
7	6.55	150.31	0.0498	3.065
8	6.52	154.96	0.0514	3.032

Table VI
Location 2 December 2007

Sample	pH	σ (μS/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.79	173.50	0.0564	2.901
2	6.76	175.86	0.0572	2.868
3	6.72	179.41	0.0584	2.836
4	6.69	182.37	0.0594	2.803
5	6.64	184.73	0.0602	2.770
6	6.57	188.57	0.0615	2.737
7	6.53	192.71	0.0629	2.721
8	6.49	194.47	0.0635	2.721

Table VII
Location 2 March 2008

Sample	pH	σ (μS/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.81	162.09	0.0532	2.639
2	6.78	165.61	0.0544	2.622
3	6.74	167.66	0.0551	2.573
4	6.69	170.30	0.0560	2.524
5	6.64	174.98	0.0576	2.475
6	6.58	176.44	0.0581	2.442
7	6.53	179.66	0.0592	2.409
8	6.47	182.28	0.0601	2.377

Table VIII
Location 3 December 2006

Sample	pH	σ (μS/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.85	79.42	0.0261	3.278
2	6.80	81.18	0.0267	3.245
3	6.93	85.27	0.0281	3.213
4	6.91	87.90	0.0290	3.18
5	6.79	92.27	0.0305	3.163
6	6.86	93.14	0.0308	3.147
7	6.82	94.30	0.0312	3.131
8	6.77	95.76	0.0317	3.114

Table IX
Location 3 December 2007

Sample	pH	σ (μS/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.85	89.90	0.0286	3.213
2	6.80	93.83	0.0299	3.180
3	6.93	97.45	0.0311	3.147
4	6.91	101.37	0.0324	3.131
5	6.79	105.88	0.0339	3.081
6	6.86	110.09	0.0353	3.065
7	6.82	113.38	0.0364	3.065
8	6.77	113.87	0.0364	3.049

Table X
Location 3 March 2008

Sample	pH	σ (μS/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.89	107.14	0.0346	3.081
2	6.83	111.31	0.0360	3.032
3	6.93	113.69	0.0368	3.016
4	6.82	116.66	0.0378	3.000
5	6.79	118.44	0.0384	2.983
6	6.92	121.71	0.0395	2.95
7	6.85	127.04	0.0413	2.934
8	6.81	129.70	0.0422	2.918

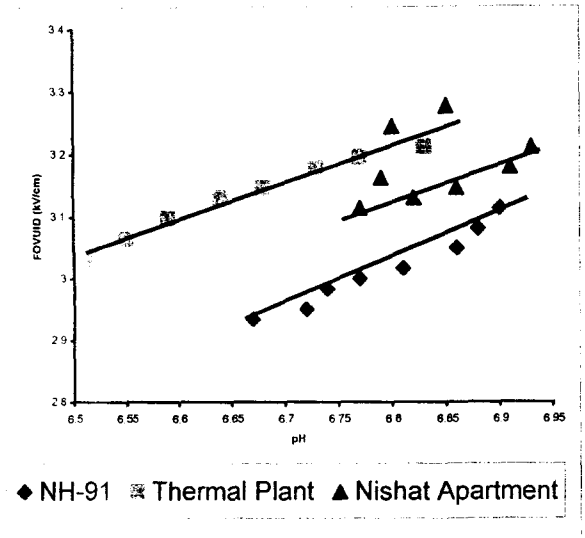

Figure 1 Variation of FOVUID with pH (December 2006)

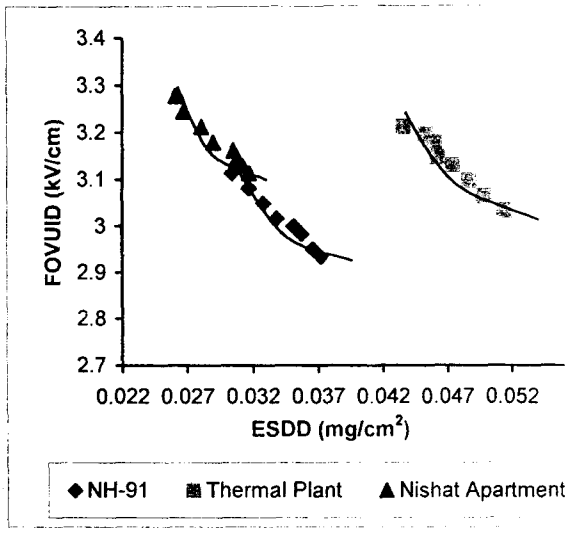

Figure 4 Variation of FOVUID with ESDD (December 2006)

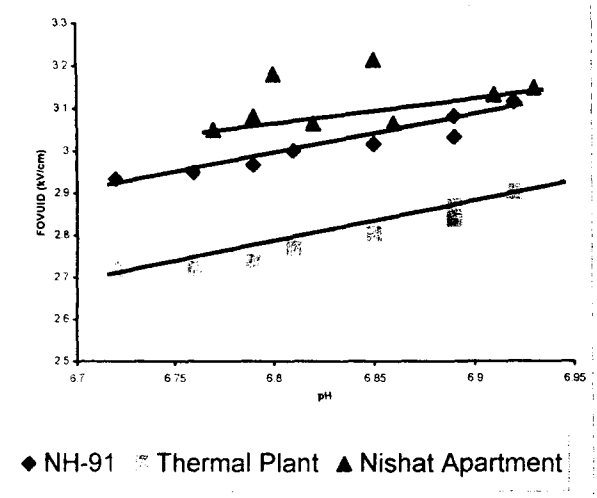

Figure 2 Variation of FOVUID with pH (December 2007)

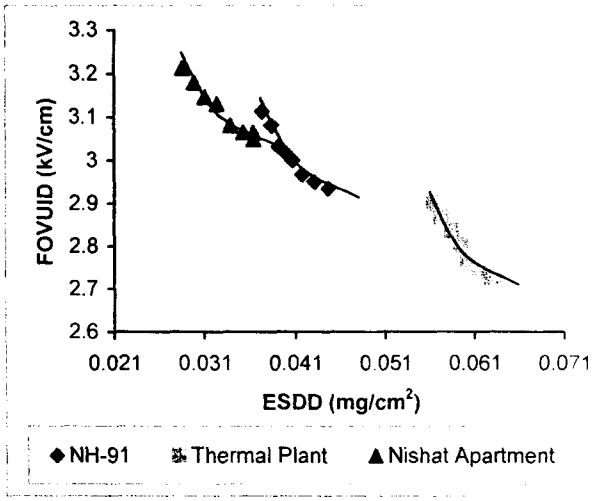

Figure 5 Variation of FOVUID with ESDD (December 2007)

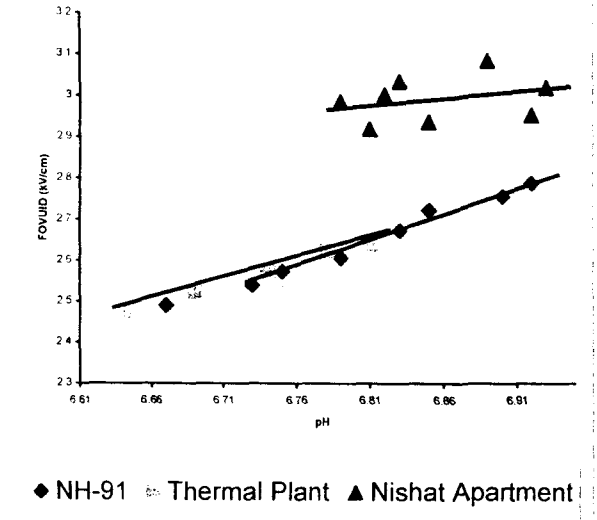

Figure 3 Variation of FOVUID with pH (March 2008)

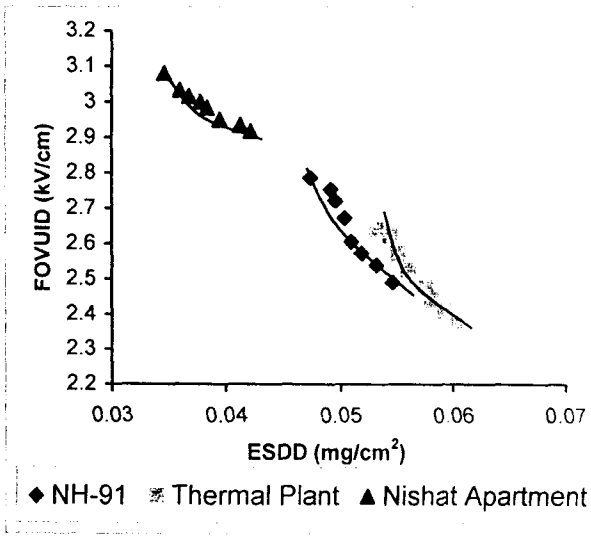

Figure 6 Variation of FOVUID with ESDD (March 2008)

VI. CONCLUSIONS

It can be concluded that pH, Conductivity (ESDD) of contaminant plays an important role in deciding the flashover voltage of the insulator. The factors influencing FOV can be summarized as:

a. The flashover voltage of an insulator depends on the environment in which it is installed.
b. Insulation requirement must be tailored to the needs of each specific case.
c. For above objective to be achieved, continuous condition monitoring of insulators is essential.
d. An increase in pH value of contaminant results in substantial increase in FOV.
e. An increase in ESDD results in considerable decrease in flashover voltage.
f. Difference in pH is due to nature of deposit.
g. Even for same ESDD, flashover voltage may be different owing to occurrence of major non soluble components in the dispersed pollutants.
h. Relative humidity plays a major role in deciding flashover characteristics.

Thus continuous monitoring of pH and conductivity, which is an indication of pollution severity of deposits on insulators, can be used for preparation of preventive maintenance schedule. Further pH monitoring can be used as a Diagnostic tool for devising a maintenance schedule as soon as pH of prevalent contaminant exceeds a predetermined value.

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A Study of Flashover Voltage of Artificially Polluted Porcelain Disc Insulator under Natural Fog Conditions

Asfar Ali Khan*, Aejaz Masood and Ekram Husain
Department Of Electrical Engineering, Aligarh Muslim University, Aligarh, India
*Email: asfaralikhan@gmail.com

Abstract--**The availability of cheap and reliable supply of electrical energy plays very important role in the economic development and social welfare of any society. Overhead power transmission lines cross regions which are different in environmental conditions. The reliable and uninterrupted operation of modern power system depends on reliable insulation. Therefore outdoor insulation cannot be selected without having knowledge of prevailing pollution severity. This paper reports results of artificial pollution tests that have been done with different contaminants. The choice of contaminants for use in the present artificial pollution test was done with respect to the occurrence of soluble and non-soluble salts in natural pollution conditions. Flashover voltage (FOV) of porcelain disc insulator for different pH values and conductivity has been recorded to relate FOV with pH and conductivity of the contaminants. It is found that an increase in pH and conductivity of the contaminants lower FOV of the insulators. Regular condition monitoring of porcelain insulators can be done using pH of the contaminants as an effective pollution severity indicator, it may further be used for devising proper maintenance schedule.**

Index Terms--**Artificial pollution test, Conductivity, FOV, Hydrated Ions, pH value, Porcelain insulators.**

I. INTRODUCTION

Overhead power transmission lines generally cross-regions that are different in topography, climate and environment. The reliable and uninterrupted operation in modern power system depends on a reliable insulation. This insulation not only must withstand over voltages but also must never deteriorate to allow disturbances, flashovers or line outages. The deterioration of outdoor insulation is caused mainly by airborne deposits that stem from natural as well as man made sources [1].

The insulators used in overhead electrical power transmission lines are susceptible to contamination-induced flashover. Outdoor insulators are subjected to pollution by dirt and chemical fumes in industrial areas, saline deposits near seacoast, desert salts as well as natural deposits in the presence of atmospheric moisture, lead to deterioration of insulation capability [2]. The resultant flashover and line outages represent large-scale economic waste. Thus the problem of selecting suitable insulators for differently polluted locations is a pressing one. Selection of outdoor insulation in a new environment is a difficult task without having some knowledge on the pollution severity of prevailing pollution. The problem becomes rather acute at higher levels of transmission voltages where over insulation is not practical due to technical (reduced BIL) and economic constraints. It is, therefore, imperative to have a reasonably accurate assessment of site severity for a technically sound design. Areas where transmission lines already exist, measurement of site severity is required to economically control the type and frequency of maintenance procedures. Regular monitoring of pollution severity is essential as several factors that contribute to atmospheric pollution may change [3].

To study insulator behavior under pollution and for improvement of insulator design proper testing under natural operating conditions is required. Adequate results are difficult to obtain from tests in natural conditions, and therefore natural pollution conditions are simulated artificially [4].The choice of contaminant for use in the present artificial pollution test was done with respect to the occurrence of soluble and non-soluble salts in natural pollution conditions. The samples were coated with salt slurry using dipping technique and were wetted under natural dew /fog condition. The flashover voltage, conductivity and pH, which is defined as the negative logarithm of the hydrogen ion activity of the solution of the contaminant, were recorded.

II. TESTING METHODS

If large power systems are to be operated with a minimum of outages a carefully planned scheme of field testing, supplemented by laboratory investigation is essential [5]. In the natural pollution testing of porcelain disc insulators, they are exposed to conditions of natural contaminations/deposits. Since dry deposits are non-conducting therefore are not a threat, but if wet, as water is a pollutant [4] the deposits lower the insulation strength. The exposure period for natural testing is large and is affected by ambient conditions. Owing to the above reasons artificial contamination tests on porcelain insulators dates before 1939[6]. In the artificial testing method the prevalent pollutants in different areas such as water soluble salts sodium chloride, potassium chloride, sodium sulphate, magnesium sulphate etc and non-soluble salts calcium oxide, magnesium oxide etc are used [7]. The deposition of the above single, multi salts can be done by number of techniques [8, 9] and their electrical and chemical properties are recorded.

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III. SAMPLE PREPARATION

In the present study the test were carried out using the cap and pin type insulators that are extensively used in overhead networks in India. The unit diameter is 254 mm, spacing 127 mm and leakage distance 290 mm.

The surfaces of the specimen insulator were cleaned and washed with detergent to remove repellency. The pretreated insulators were thoroughly contaminated with contaminants such as Sodium Chloride (NaCl), Potassium Chloride (KCl), Magnesium Sulphate ($MgSO_4$) and Calcium Oxide (CaO) using the dipping technique. The contaminant slurry was obtained by adding salts of amounts as indicated in Tables I-IV to two liters of water. After dipping the samples in contaminant solution for 2 hours, they were taken out for drying in sunlight. The dried samples were left to get wet under natural conditions of dew and fog from 6 pm to 9 am during December month at Aligarh. (India)

IV. MEASUREMENT

The flashover voltage of the sample was measured in morning hour (Temperature around 15°C & pressure 740 mm Hg) using high voltage testing transformer. The contaminants were removed from the sample and the pH and conductivity of the pollutant measured.

A. Voltage Measurement

The high voltages were obtained from a testing transformer of 150 kV, 50 Hz, 1-phase, 30 kVA rating. The short circuit current of the testing transformer is 15 A at maximum excitation. The voltages were measured using a voltmeter (accuracy ± 1%) connected to the primary side of the transformer, that reads the low side voltage. The corresponding high voltages are obtained from a calibration curve drawn by using the sphere – sphere electrode system having diameter of 25 cm (IS: 1876-1963).

B. Measurement of pH

The pH value of the contaminant was measured after removing deposited salt on the sample using LI 120 pH meter with range from 0-14.

C. Measurement of Conductivity

The conductivity of the contaminant deposited on the surface of the insulators was measured using CM 180 conductivity meter having cell constant 0.1 to 1 and conductance range 20 µS to 200 mS.

V. RESULTS AND ANALYSIS

The contaminated insulators after being exposed to natural wet conditions were subjected to high voltage for recording wet flashover voltage. The observed value of flashover voltages, conductivity and pH are given in Tables I-IV

The variation of Flashover Voltage and pH value of the contaminant for different salts are given in Figure 1. It can be seen that a very small increase in pH value results in substantial decrease in flashover voltage such as for 0.05 changes in pH of NaCl results in about 13% change in Flashover voltage.

The variation of Flashover Voltage and conductivity of the contaminant for different salts are given in Figure 2. It is observed that FOV of $MgSO_4$is higher than NaCl. This variation is attributed to the fact that solubility NaCl is higher than $MgSO_4$.

The chemical combination of the salt mixture plays a decisive role in influencing the flashover voltage. It is observed that when CaO which is non soluble in water is added to NaCl, for same pH value of NaCl and NaCl+CaO the Flashover voltage for NaCl+CaO is higher.

It can be seen from the Figure 1 that the flashover voltage falls with increase of pH value of the contaminant. Increase of pH implies increase in hydroxyl ions leading to basicity of the contaminant and so flashover occurs at a lower voltage. [10]

Further Figure 2 clearly indicates that as the conductivity increases the flash over voltage decreases. This may be attributed to the fact that conducting electrolytes are formed depending on degree of solubility of a salt. It can be further explained in terms of the process of hydration in which the ions get surrounded by water molecules. These hydrated ions moves freely in solution and their ability to move explains the conductivity of salt species. The extent of hydration depends on the size of the ion. Wherein it has been seen that smaller the size of the ion, more it is hydrated and hence greater is its ionic radii which results in lesser ionic mobility, as can be seen that the drop in FOV of KCl is more than NaCl [Figure 2]. This is due to the fact that ionic radii of potassium ion is greater than sodium ion and hence the ionic mobility of potassium ion is greater than sodium ion.[10-12]

Also for multi salt combination [13] the flashover voltage depends on the relative weights of the soluble and/or non-soluble components. (Table III).

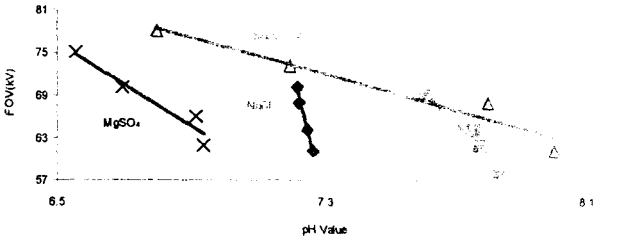

Figure 1. Variation of FOV with pH of Contaminants

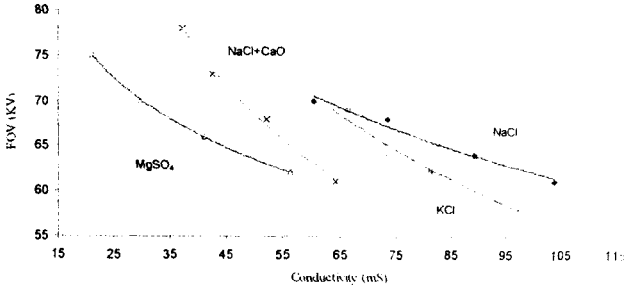

Figure 2. Variation of FOV with conductivity of Contaminants

VI. CONCLUSIONS

It can be concluded that pH and Conductivity of contaminant plays an important role in deciding the flashover voltage of the insulator. The factors influencing FOV can be summarized as:

a. An increase in pH value of contaminant results in substantial decrease in FOV.
b. Degree of hydration in salt ions influences the FOV.
c. Solubility of salt plays a major role in deciding the variation of FOV.
d. Chemical combination of salts in a mixture influences FOV.

Thus continuous monitoring of pH and conductivity, which is an indication of pollution severity of deposits on insulators, can be used for preparation of preventive maintenance schedule. Further pH monitoring can be used as a Diagnostic tool for devising a maintenance schedule as soon as pH of prevalent contaminant exceeds a predetermined value.

Table I
NaCl as Contaminant

S.No	NaCl (gm)	Conductivity (mS)	pH Value	Wet flashover voltage (kV)
1	76.6	60.50	7.22	70
2	88.6	73.63	7.23	68
3	112.3	89.36	7.25	64
4	138.3	103.93	7.27	61

Table II
KCl as Contaminant

S.No	KCl (gm)	Conductivity (mS	pH Value	Wet flashover voltage (kV)
1	66.6	66.70	7.60	69
2	84.0	73.20	7.75	64
3	121.1	81.35	7.77	62
4	135.6	98.65	7.83	58

Table III
NaCl + CaO as Contaminant

S.No	NaCl +CaO (gm)	Conduct-ivity (mS	pH Value	Wet flashover voltage (kV)
1	76.6+34.9	37.3	6.79	78
2	88.6+34.9	42.6	7.20	73
3	112.3+34.9	52.1	7.81	68
4	138.3+34.9	64.3	8.00	61

Table IV
$MgSO_4$ as Contaminant

S.No	$MgSO_4$ (gm)	Conductivity (mS)	pH Value	Wet flashover voltage (kV)
1	48.37	21.20	6.56	75
2	96.32	29.70	6.70	70
3	113.55	41.25	6.92	66

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Metro, train services, water supply hit in city after Northern Grid partially trips

Capital hit hard by untimely fog

Moushumi Das Gupta
New Delhi, March 8

METRO AND train services and water supply were hit in the Capital on Friday after the Northern Grid, from which Delhi draws power heavily, partially tripped.

Reeling under a shortfall of 1,500 MW, almost the entire city except Lutyen's Delhi and some other areas suffered massive outages between six and 11 hours. The worst-affected areas were west and east. Power supply was restored and the situation bought under control by mid-noon.

It was an unusual culprit for this time of the season that was blamed for the breakdown. Senior officials of the Northern Region Load Dispatch Centre (NRLDC) said dense fog and pollutants accumulated on the transmission lines of the Northern Grid and caused massive tripping, disrupting power supply, rail and metro traffic and water supply. Forty-nine transmission lines in the Northern Grid tripped.

A Delhi Transco spokesman said in all, six 400KV lines tripped in Delhi resulting in a shortfall of 1,500MW in the Capital during the early hours of Friday. "At around 4 a.m., the lines carrying power from Rihand, Singrauli, Tala to Dadri and Delhi tripped causing a shortfall of 1,500MW. Forty-nine 400KV Power Grid lines tripped, including six in Delhi area," said the DTL spokesman.

He added, "The Badarpur Thermal Power Station, Rajghat Power House and IP station escaped the breakdown to ensure supply to south and central Delhi. Complete normalisation was only possible after the Dadri Thermal Power Station supplying power to Delhi was restored around noon."

The worst-affected were east and west Delhi. "The lights went off at 1.30 a.m. and came only after 11.30 a.m. We called the local complaint centre but, as usual, the phones lines were put off the hook," said Suhasini Nair, a Patparganj resident. Areas like Mayur Vihar, Vasundhara, Patparganj, Dwarka, Janakpuri, Paschim Vihar, Pitampura, Daryaganj went without power for 10 hours at a stretch.

This is not the first time power lines in the Capital tripped due to fog. "It's a recurrent problem during winter months. But we were not expecting it during this time of the year. Apart from the fog, what aggravated the problem was the high humidity content. Moisture accumulated in the 400KV transmission lines, which resulted in tripping," said a power department official.

moushumi.gupta@hindustantimes.com

Good old diesel engines to rescue

HT Correspondent
New Delhi, March 8

THE RAILWAYS, perhaps for the first time, used diesel-run locomotives to pull electric-run local trains like tow-away vehicles, and kept services afloat when the power grid collapse severely affected the rail network.

Power supply to the rail network was unavailable for two to four hours in the morning. "The priority were local trains in the morning because they bring thousands of people into the Capital from different parts every day," said a senior railway official. Since electricity was scarce and the demand high, the movement of all goods trains was temporarily suspended. As an additional measure, all long-distance trains heading towards Delhi were instructed to stop at suburban stations to accommodate daily passengers.

Metro services affected

Tripping of six transmission lines in Delhi also affected the Metro services. According to Delhi Metro Rail Corporation (DMRC) officials, the voltage suddenly dipped causing disruption of metro at about 6.30 a.m. on Line 1 (Shahdara-Rithala) and Line 3 (Indraprastha-Drawka).

A senior DMRC official said the disruption of metro service was for a very few minutes. The situation was immediately normalised, by drawing the supply from metro's Indraprastha and New Delhi sub-stations.

letters@hindustantimes.com

Fog trips Northern Grid

Twenty-five trains, including Rajdhani, Shatabdi delayed

New Delhi, March 7

LARGE PARTS of the capital went without power since early morning on Friday as 50 supply lines of the Northern Grid, which supplies power to Delhi and neighbouring areas, tripped due to fog.

A six-hour power outage followed by another six hours for electricity supply to be restored affected most parts of Central, East and South Delhi and train services.

A spokesman for the Northern Regional Load Dispatch Centre (NRLDC) of the Power Grid Corporation said 50 lines of 400 kv in Delhi's Bawana-Bamroli-Mandola line, western Uttar Pradesh and Haryana tripped at about 3 a.m. The system was restored at about 9 a.m., he added.

The engineers were suspecting the snag was due to heavy fog that had got the high-tension wires wet.

Train movement in the national capital and its vicinity was also affected due to the power cut. "Traffic in the region was badly affected by the power failure, with the worse affected sections being Ferozabad-Dadri and Tughlakabad-Palwal lines, where electricity supply was disrupted since 3.45 am and 6.15 am respectively," a senior Railway official said.

"The electricity supply to the overhead cable, which supplies power to the engine, was completely down, bringing the movement of trains to a halt," he added.

The officials said the Railways was taking all emergency measures and diesel engines were being dispatched to resume services.

Rajeev Saxena, chief public relations officer of Northern Railways said 25 trains had been delayed in a big way, including Rajdhani and Shatabdi trains between the capital and various cities. However, trains from New Delhi, Nizamuddin and Delhi stations that were scheduled for the afternoon and evening would leave as per schedule.

Agencies